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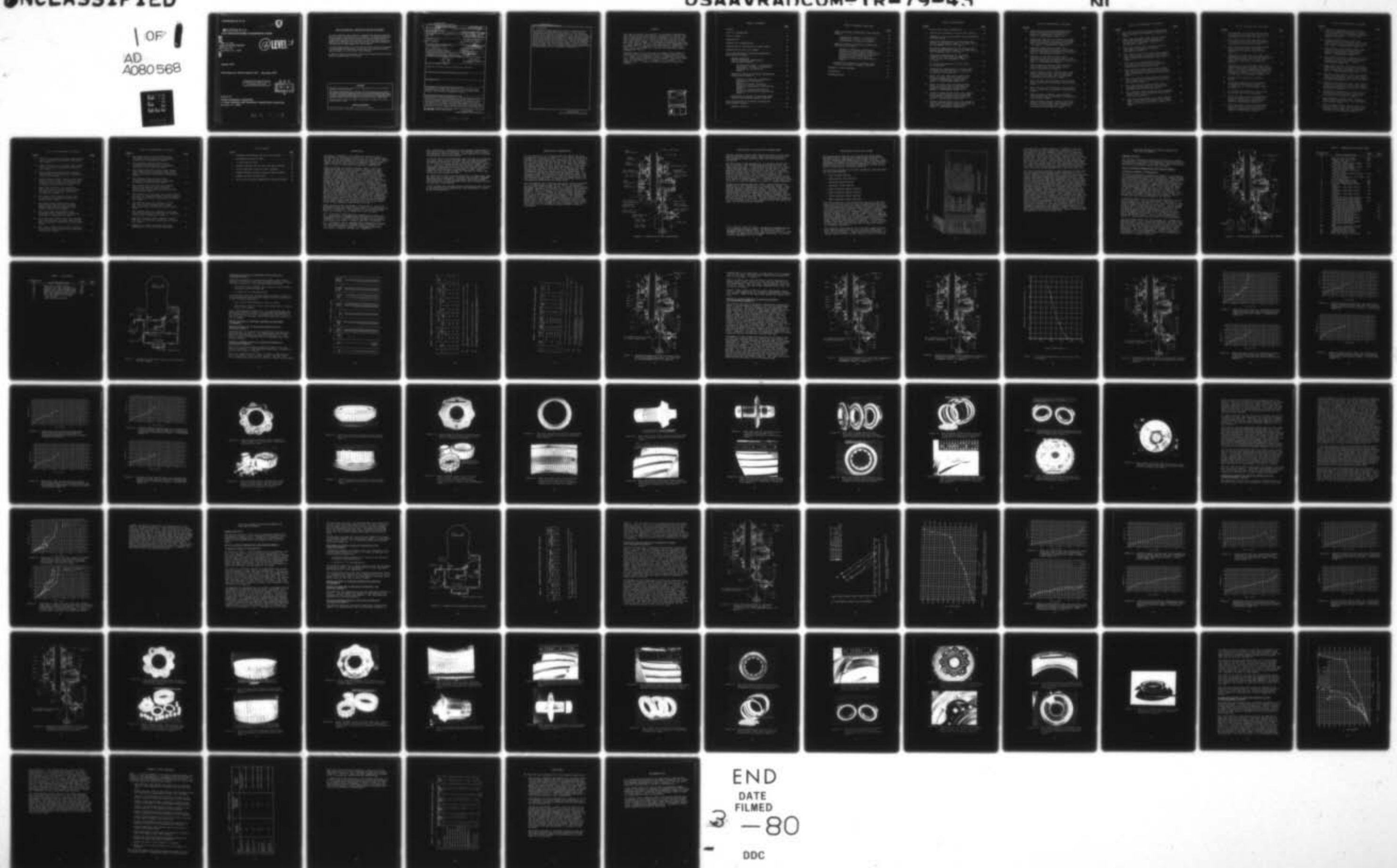

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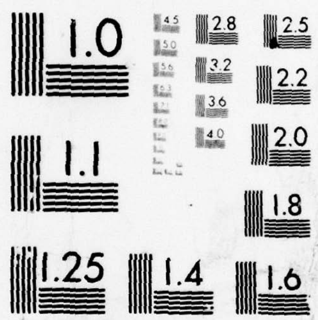

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AH-1S HIGH-SURVIVABLE TRANSMISSION SYSTEM

(12) LEVEL III

Gary A. Cope
BELL HELICOPTER TEXTRON
P.O. Box 482
Fort Worth, Tex. 76101

October 1979

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APPLIED TECHNOLOGY LABORATORY
U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report presents the results of tests on a modified AH-1S transmission designed to operate in excess of 30 minutes after loss of lubrication. The design tested has shown an improvement (in operation time) of from seven to fifty-four minutes over the standard AH-1S design after loss of lubrication. The tests have further indicated that attainment of the 30-minute goal has been achieved for all transmission components at load levels within the flight envelope of the AH-1S helicopter.

This report presents a design of an AH-1S main transmission to improve the survivability of the AH-1S after loss of lubrication. Incorporation of this design will provide the needed survivability in all of the AH/UH-1 Army helicopters.

Mr. Wayne A. Hudgins of the Propulsion Technical Area, Aeronautical Technical Division served as the project engineer for this project.

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The objective of the work performed on this program was to demonstrate that the AH-1S main transmission system, modified with internal component improvements but without an emergency lubrication system, could operate for 30 minutes following the loss of lubrication. The internal component improvements were based upon work done under this program and work done under a previous Eustis Directorate contract, both conducted by Bell Helicopter Textron.

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Six different modified versions of the AH-1S transmission configuration were tested under this program. Four of the six transmission configurations had been run to failure previously and the results reported in USAAMRDL-TR-77-30. The loss-of-lube testing for the final two transmission configurations was conducted at 680 input horsepower (60 percent of maximum continuous power rating of the AH-1S) and 6600 input rpm. The first transmission configuration tested ran 25 minutes under loss-of-lube conditions before failure of the lower planetary stage. The second transmission configuration ran 54 minutes before failure of the lower planetary stage. Thus, the 30-minute loss-of-lube capability has been demonstrated for all transmission components.

PREFACE

This report contains the results of a program to demonstrate that the AH-1S main transmission, modified with internal component improvements but without an emergency lubrication system, could operate for 30 minutes following the loss of the main lubrication system. This program was conducted by Bell Helicopter Textron (BHT) for the Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM) from September 1977 to December 1978 under Contract DAAJ02-76-C-0006. Prior work under this contract was reported in Report USAAMRDL-TR-77-30.

AVRADCOM technical direction was provided by Wayne Hudgins. This program was conducted under the technical direction of G. A. Cope, Project Engineer, and C. E. Braddock, Group Engineer, Transmission Research and Development. Technical assistance was provided by R. J. Bryson, T. J. Gerlach, J. D. Loggins, and L. O. Wood of the BHT Transmission Bench Test Facility.

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

INTRODUCTION

An important parameter in the design of utility/tactical helicopters is survivability after loss of drive system lubrication. Design refinements and testing are required to improve the ability of the helicopters to complete their missions in combat situations after sustaining ballistic damage that result in loss of lubrication on the main transmission.

Under a previous contractual research effort, tests were conducted at BHT on a high survivable transmission (HST) system for the AH-1G/Q helicopter.[1] This sytem included component improvements as well as an emergency lubrication system. The design goal under the previous contract (Eustis Directorate Contract DAAJ02-74-C-0019) was to achieve 60 minutes of transmission operation at best cruise condition after the loss of normal lubrication. In actual tests at 950 horsepower input (84 percent of maximum continuous power rating) and 6600 rpm, the high-survivable transmission system for the AH-1G/Q operated successfully for 4.0 hours following the loss of the normal lubrication. After approximately 1-1/2 hours of the emergency lubrication test run, the emergency oil supply was exhausted and thus the remaining 2-1/2 hours of the test run were completed with no lubrication system functioning. The test indicated that the improved transmission components in the form of silver-plated steel retainers for the bearings, CEVM M-50 steel rollers and roller guides in the planetaries, plus increased outer race curvature (and internal clearance) of the input triplex bearing may have been the major contributors to the extensive loss-of-lube run time.

Under work previously performed on this contract, tests were conducted at Bell Helicopter Textron (BHT) on an HST system for the AH-1S helicopter.[2] The objective of the work performed under this contract was to demonstrate that the AH-1S

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[1]D. J. Richardson, HIGH-SURVIVABLE TRANSMISSION SYSTEM, Bell Helicopter Textron, USAAMRDL Technical Report 76-8, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, May 1976, AD A025930.

[2]D. J. Richardson, AH-1S HIGH-SURVIVABLE TRANSMISSION SYSTEM, Bell Helicopter Textron, USAAMRDL Technical Report 77-30, U.S. Army Air Mobility Research & Development Laboratory, Fort Eustis, Virginia, October 1977, ADA047558.

main transmission, modified with the component improvements of the high survivable transmission for the AH-1G/Q but without the emergency lubrication system, could operate for 30 minutes following the loss of lubrication.

In actual tests at 950 horsepower input (84 percent of maximum continuous power rating) and 6600 rpm, the high survivable transmission system for the AH-1S operated successfully for 7, 21, 19, and 26.5 minutes following the loss of normal lubrication. The tests indicated that the improved transmission components increased the loss-of-lube run time but additional component modifications or a reduction in power level to reduce the rate of heat buildup are required to achieve the 30-minute loss-of-lube run time.

The objective of this follow-on effort was to demonstrate that the AH-1S main transmission, modified with internal component improvements but without the emergency lubrication system, could operate at an optimum power level for 30 minutes following the loss of lubrication.

A test program that included loss-of-lubrication tests on each of two modified AH-1S transmissions was undertaken to accomplish the program goal.

PRESENT AH-1S TRANSMISSION

A cross sectional view of the present Bell AH-1S type main transmission is shown in Figure 1. It is similar to the UH-1 configuration and consists of a bevel gear set at the main input from the engine that drives the main rotor mast through two epicyclic planetary gear trains. The gear ratio between the engine and main rotor is 20.383 to 1. Tail rotor power is transmitted through the main input gearshaft to a spur gear set and then through a bevel gear set, located in the main transmission sump case, to the tail rotor driveshaft. The transmission rating for maximum continuous power (MCP) is 1134 shp at 6600 rpm and its rating for takeoff, hover, and low-speed flight is 30 minutes at 1290 shp at 6600 rpm. The accessory drives incorporated on the main transmission are a dual hydraulic pump drive, a tachometer generator drive, and a heating and ventilating fan blower drive.

The transmission has a wet-sump lubrication system consisting of a 10.5-gpm pressure pump, an oil cooler, an automatic emergency oil cooler by-pass system, a pressure relief valve and bypass manifold, oil filters, jets, valves, and associated hardware. The oil capacity of the transmission lubrication system is 11 quarts. Except for the oil cooler and the emergency oil cooler bypass, the lubrication system components are integral to the transmission assembly. The automatic emergency oil cooler bypass system consists of a balanced piston device that operates when low pressure exists in the cooler loop. With this system, if the cooler and its associated lines are hit or begin to leak, the bypass valve routes oil directly to the transmission upon sensing a pressure difference.

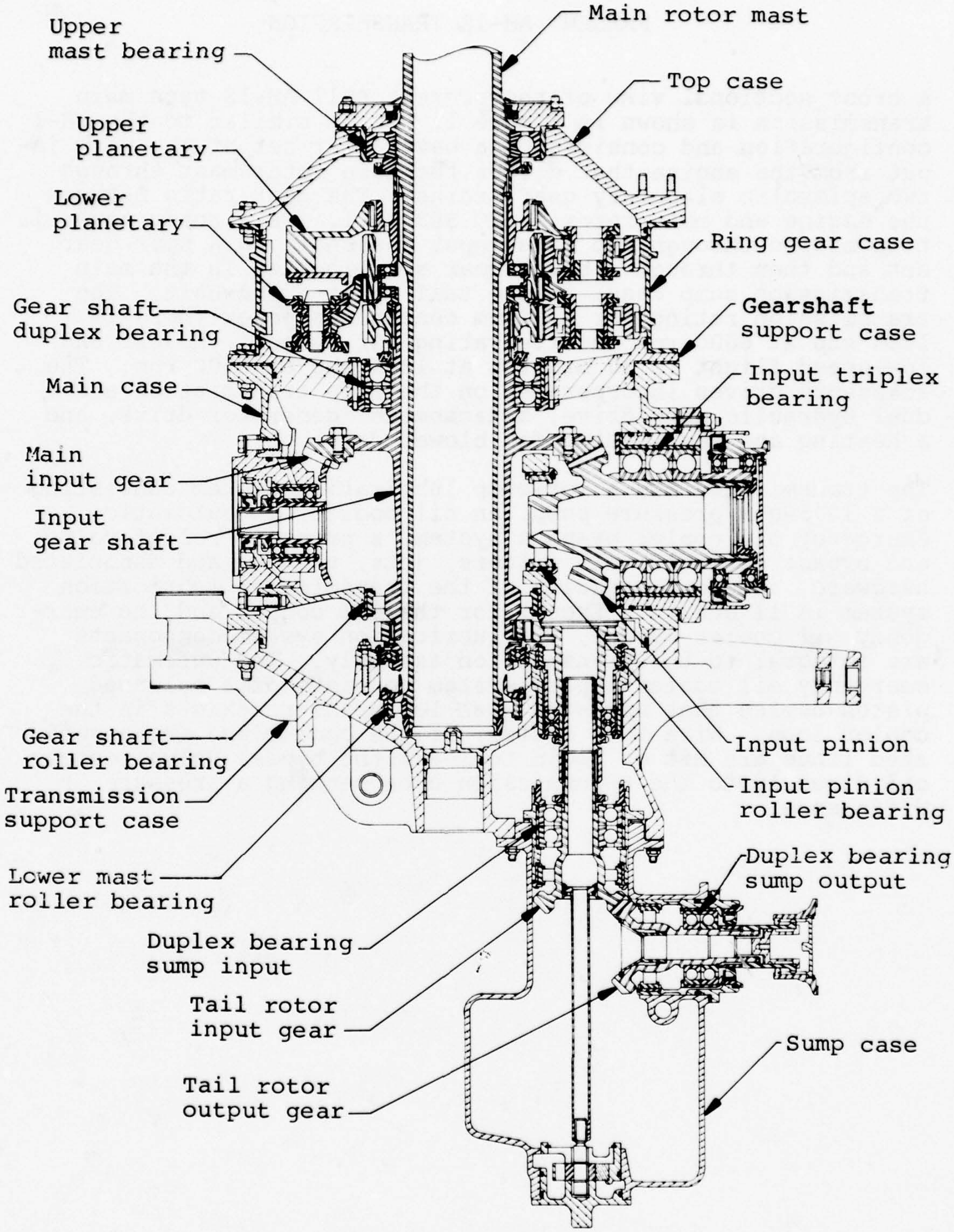

Figure 1. Typical AH-1S type transmission.

DESCRIPTION OF SURVIVABILITY PROBLEM AREAS

Previous research efforts have defined the areas of the transmission that would most likely limit the time-to-failure of the transmission when operating under loss-of-lubrication conditions.[3]

The main input to the transmission is a primary problem area due to the high loads and the high operating speeds of the input bevel gear set. A triplex ball bearing set and a single roller bearing support a bevel pinion in this quill. Heat generation after loss of lubricant in this area is extremely high and, historically, the life of this quill is only 7 to 9 minutes following loss of the lubrication system. The mode of failure in this area is usually either seizure of the triplex ball bearing due to loss of internal bearing clearance as a result of thermal expansion, or failure of the bevel pinion teeth due to loss of backlash as a result of thermal expansion.

Another major problem area that limits loss-of-lubrication capability of the transmission is the planetary system. High sliding velocities combine with high centrifugal loads in this area to generate large amounts of heat. The lower planetary assembly contains bronze roller bearing retainers that have low strength in the high temperature range of marginal lubrication or dry operation. The upper planetary assembly contains nylon roller bearing retainers that are severely limited by the melting point of the nylon. Previous testing had indicated a 6- to 12-minute life for the planetary system when operating under loss-of-lubrication conditions.

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[3] J. H. Drennan, and R. D. Walker, TRANSMISSION THERMAL MAPPING (UH-1 MAIN ROTOR TRANSMISSION), Bell Helicopter Textron; USAAMRDL Technical Report 73-90, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, December 1973, AD 777803.

DESCRIPTION OF AH-1S HST SYSTEM

The transmissions used for this program were UH-1D types modified to AH-1S configurations and further modified with the HST component improvements as described in Table 1. The component improvements incorporated on these two transmissions were based on results of work performed by BHT under Contract DAAJ02-74-C-0019 with the Eustis Directorate, as well as results of other BHT oil starvation testing.

The following bearings in the main transmission were modified for this test program:

- Input triplex bearing
- Input pinion roller bearing
- Gearshaft duplex bearing
- Gearshaft roller bearing
- Lower planetary support bearing
- Upper planetary support bearing
- Lower planetary planet bearings
- Upper planetary planet bearings

With the exceptions of the triplex ball bearing in the main input quill and the upper and lower planetary bearings, the bearing modification in each instance consisted of installing a silver-plated steel bearing retainer in place of the standard bronze or nylatron retainer. The maximum recommended operating temperature for a machined bronze or a nylatron bearing retainer is 275°F, whereas a machined steel cage can operate at temperatures as high as 800°F. These recommended operating temperatures are for properly lubricated conditions, but the machined steel cage (being stronger at normal and higher operating temperatures) is superior to the bronze or nylatron cage under loss-of-lube conditions. Silver plating of the steel cage adds lubricity that is necessary during oil starvation operation.

The standard triplex bearing set in the main input quill has balls and races made of M-50 steel and has silver-plated steel bearing retainers. Under loss-of-lube conditions, the typical mode of failure of this bearing is loss of internal

TABLE 1. COMPONENT MODIFICATION FOR AH-1S HST TESTING

TEST 1	RETEST OF 1	TEST 3	TEST 4	EXPLORATORY TEST 1A	EXPLORATORY TEST 1B	EXPLORATORY TEST 1C	OPTIMIZED TEST 1	OPTIMIZED TEST 2	PART NUMBER AND/OR DESCRIPTION	MODIFICATIONS/SUBSTITUTIONS
				•	•	•	•	•	204-040-129-1 UPPER PLANETARY BRG. CAGE (NYLON)	SUBSTITUTED 204-040-133-1 CAGE (BRONZE)
•	•	•	•						204-040-129-1 UPPER PLANETARY BRG. CAGE (NYLON)	SUBSTITUTED 300-040-168-3 CAGE (SILVER-PLATED STEEL)
			•						204-040-132-1 LOWER PLANETARY BRG. INNER RACE	.0005 INCH UNDERSIZE O.D. AND M-50 STEEL IN LIEU OF 52100 STEEL
•	•	•	•	•	•	•	•	•	204-040-133-1 LOWER PLANETARY BRG. CAGE (BRONZE)	SUBSTITUTED 300-040-168-3 CAGE (SILVER-PLATED STEEL)
•	•	•	•	•	•	•		•	204-040-134-5 LOWER PLANETARY ROLLER GUIDE	M-50 STEEL IN LIEU OF AMS6260 STEEL
•	•	•	•	•	•	•		•	204-040-134-5 UPPER PLANETARY ROLLER GUIDE	M-50 STEEL IN LIEU OF AMS6260 STEEL
•	•	•	•	•	•	•	•	•	204-040-135-1 LOWER PLANETARY SUPPORT BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF BAKELITE CAGE
•	•	•	•						204-040-135-1 **T/R TAKEOFF BALL BRG.**	SILVER-PLATED STEEL CAGE IN LIEU OF BAKELITE CAGE
•	•	•	•	•	•	•	•	•	204-040-135-1 UPPER PLANETARY SUPPORT BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF BAKELITE CAGE
•	•	•	•						204-040-136-9 UPPER MAST BALL BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF BRONZE CAGE
								•	204-040-261-13 OIL JET	REWORKED BY ADDING JET ORIFICE TO SUPPLY OIL COLLECTOR
•	•	•	•						204-040-270-3 LOWER MAST ROLLER BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF BRONZE CAGE
•	•	•	•	•	•	•	•	•	204-040-271-3 LOWER GEAR SHAFT ROLLER BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF BRONZE CAGE
								•	204-040-359-1 TOP CASE	REWORKED BY ADDING TAPPED HOLES FOR OIL COLLECTOR
•	•	•	•						204-040-424-1 **T/R TAKEOFF DUPLEX BRG.**	SILVER-PLATED STEEL CAGE IN LIEU OF NYLATRON CAGE
•	•	•	•					•	204-040-725-1 LOWER PLANETARY ROLLER SET	M-50 STEEL IN LIEU OF 52100 STEEL
•	•	•	•						204-040-725-1 UPPER PLANETARY ROLLER SET	M-50 STEEL IN LIEU OF 52100 STEEL
							•		205-040-229-1 LOWER SUN GEAR	SUBSTITUTED 699D-20-1 NARROW FACE WIDTH, CROWNED, SUN GEAR
			•						205-040-229-1 LOWER SUN GEAR	SUBSTITUTED 209-040-031-1 NITRIDED SUN GEAR
•	•	•	•	•	•	•	•	•	205-040-245-1 INPUT GEAR SHAFT DUPLEX BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF NYLATRON CAGE
•	•	•	•	•	•	•	•	•	205-040-246-3 MAIN INPUT TRIPLEX BRG.	INCREASED OUTER RACE CURVATURE FROM 52% TO 54%
•	•	•	•	•	•	•	•	•	205-040-249-1 INPUT PINION ROLLER BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF BRONZE CAGE
•	•	•	•						212-040-143-1 T/R DRIVE, SUMP OUTPUT DUPLEX BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF NYLATRON CAGE
•	•	•	•						212-040-144-1 T/R DRIVE, SUMP INPUT DUPLEX BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF NYLATRON CAGE
•	•	•	•						212-040-210-1 **T/R TAKEOFF ROLLER BRG.**	SILVER-PLATED STEEL CAGE IN LIEU OF BRONZE CAGE
•	•	•	•						212-040-210-1 T/R DRIVE, SUMP INPUT ROLLER BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF BRONZE CAGE
•	•	•	•						212-040-210-1 T/R DRIVE, SUMP OUTPUT ROLLER BRG.	SILVER-PLATED STEEL CAGE IN LIEU OF BRONZE CAGE
								•	699-458-001-101 OIL COLLECTOR	INSTALLED ABOVE UPPER PLANETARY
								•	699-458-001-103 OIL COLLECTOR	INSTALLED BETWEEN PLANETARIES
•	•	•	•						84% MC POWER	
				•	•		•	•	60% MC POWER	
						•			75% MC POWER	
•	•	•	•						CARBON RADIAL INPUT SEAL	
		•							UPPER PLANETARY BACKLASH	INCREASED BY MODIFYING PLANET PINIONS
		•							LOWER PLANETARY BACKLASH	INCREASED BY MODIFYING PLANET PINIONS
							•		LOWER PLANETARY BACKLASH	INCREASED BY MODIFYING SUN GEAR
•									INPUT BEVEL SET BACKLASH .007 INCH	
	•	•	•				•		INPUT BEVEL SET BACKLASH .012 INCH	
				•	•				INPUT BEVEL SET BACKLASH .015 INCH	
						•			INPUT BEVEL SET BACKLASH .016 INCH	
								•	INPUT BEVEL SET BACKLASH .019 INCH	
			•						699D-16-1 OIL COLLECTORS	INSTALLED BELOW LOWER PLANETARY

clearance due to thermal expansion. Therefore, the outer race curvature of this bearing was increased from 52 to 54 percent of the ball diameter, which not only increased the internal clearance of the bearing 0.003 inch but also transferred the bearing race control from the outer to the inner race. Inner race control means that ball rolling occurs at the inner race while sliding occurs at the outer race. With inner race control, this modified triplex bearing generates less heat at the inner race and more heat at the outer race than the standard triplex. This modification then tends to prevent loss of bearing clearance that occurs when the inner race heats up and expands faster than the outer race.

The lower planetary bearings in both transmissions were modified by replacing the standard bearing retainers with retainers made of silver-plated steel. The lower planetary bearings in optimized transmission configuration number 2 were further modified by replacing the standard AISI 52100 steel rollers with rollers made from CVEM M-50 steel and by replacing the standard AMS 6260 steel planetary roller guides with roller guides made of CVEM M-50 steel. The upper planetary bearings in both transmissions were modified by replacing the standard bearing retainers with retainers made of bronze. The upper planetary bearings in optimized transmission configuration number 2 were further modified by replacing the standard AMS 6260 steel planetary roller guides with roller guides made of CVEM M-50 steel. These changes were made to allow operation of the planetaries to continue even under the severe high temperature conditions that exist in a loss-of-lube environment. Since the modifications dictated by this program may be incorporated into the AH-1S transmission design, it was determined that it would be worthwhile to test the bronze retainers in the upper planetary and to use the standard rollers and roller guides in both planetaries in optimized transmission configuration number 1 because of the cost savings that would be realized if these parts functioned successfully in the loss-of-lube test.

AH-1S HST TESTING OF OPTIMIZED TRANSMISSION CONFIGURATION NUMBER 1

GENERAL OBJECTIVE

The testing of optimized transmission configuration number 1 was performed to determine the response of the modified AH-1S transmission operating at an optimum power level (60 percent MCP) after the complete loss of the oil supply.

TEST OF OPTIMIZED TRANSMISSION CONFIGURATION NUMBER 1

Transmission Number 1 Configuration

Optimized transmission configuration number 1 was assembled to a standard production AH-1S configuration, except the modifications listed in Table 1 were incorporated. Thermocouples were installed in the locations indicated in Figure 2 and Table 2 to allow monitoring of the transmission thermal characteristics during testing. Temperatures were recorded on three Digitec Data Loggers, Model 590JF, which were Type J (iron-constantan) calibration with a full range of -320°F to 1400°F. Temperatures were recorded at intervals of 1 minute or less throughout the testing. Oil pressure, oil flow, main rotor mast torque, tail rotor mast torque, and input rpm were recorded at intervals of 2 minutes. MIL-L-23699B lubricant was used throughout the testing.

A system to enable the oil cooler to be bypassed or to simulate a severed oil line was implemented. The system is shown schematically in Figure 3. Oil from the main oil sump could be pumped through any of three paths: (1) by closing valves A and C and opening valve B, the oil could be pumped through the oil cooler and back to the transmission; (2) by closing valves B and C and opening valve A, the oil could be pumped directly back to the transmission without going through the oil cooler; or (3) by closing valves A and B and opening valve C, the oil could be pumped into a remote oil tank, preventing its return to the transmission.

The test stand utilized for this program was a regenerative/absorption-type stand. Torque was applied to the main rotor mast through a regenerative loop by rotating the "slave transmission" planetary ring gear in relation to the main case. Main rotor mast torque was monitored by employing a strain-gaged mast. The tail rotor loop was loaded using a 300-horsepower water brake dynamometer. Power was supplied to the system by a 500-horsepower eletric motor and speed was regulated by a magnetic coupling.

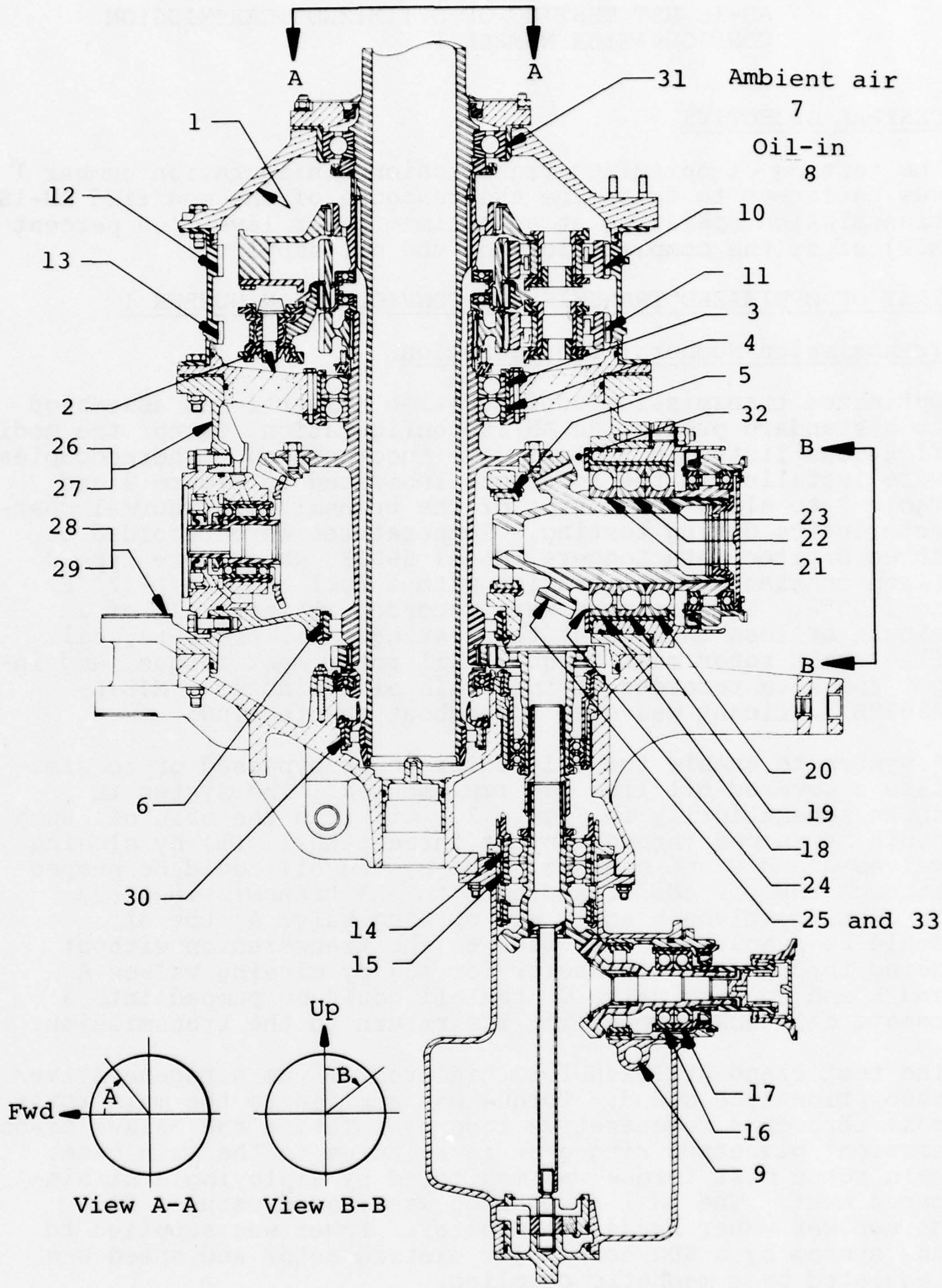


Figure 2. Thermocouple locations for AH-1S HST testing.

TABLE 2. THERMOCOUPLE LOCATION INDEX

Thermocouple No.	Location/Nomenclature	Angle A	Angle B
1	Top Case (Inner Surface)	190°	
2	Support Case, Bevel Gear (Upper Surface)	190°	
3	Bevel Gear Shaft Duplex, Upper Bearing (Outer Ring)	270°	
4	Bevel Gear Shaft Duplex, Lower Bearing (Outer Ring)	270°	
5	Input Pinion Roller Bearing (Outer Ring)		30°
6	Bevel Gear Shaft Roller Bearing (Outer Ring)	120°	
7	Test Cell Ambient Air (12 inches from main case)	270°	
8	Oil-in Temperature Probe	120°	
9	Oil-out Temperature Probe	270°	
10	Ring Gear, Upper Mesh (Tooth End)	45°	
11	Ring Gear, Lower Mesh (Tooth End)	45°	
12	Ring Gear, Upper Mesh (Tooth Root)	40°	
13	Ring Gear, Lower Mesh (Tooth Root)	40°	
14	Tail Rotor Drive Input Duplex, Upper Bearing (Outer Ring)	280°	
15	Tail Rotor Drive Input Duplex, Lower Bearing (Outer Ring)	280°	
16	Tail Rotor Drive Output Duplex, Inboard Bearing (Outer Ring)		50°
17	Tail Rotor Drive Output Duplex, Outboard Bearing (Outer Ring)		50°
18	Input Pinion Inboard Triplex Bearing (Outer Ring)		250°
19	Input Pinion Center Triplex Bearing (Outer Ring)		80°
20	Input Pinion Outboard Triplex Bearing (Outer Ring)		85°
21	Input Pinion Inboard Triplex Bearing (Inner Ring)		
22	None		
23	Input Pinion Outboard Triplex Bearing (Inner Ring)		
24	Triplex Bearing, Oil-out		
25	Input Pinion Tooth Root		
26	Main Case, Upper 1/3 Section	95°	

TABLE 2. (Concluded)

Thermocouple No.	Location/Nomenclature	Angle A	Angle B
27	Main Case, Center Section	85°	
28	Support Case, Main Transmission	85°	
29	Support Case, Main Transmission	95°	
30	Mast Roller Bearing (Outer Ring)	300°	
31	Mast Ball Bearing (Outer Ring)	120°	
32	Bevel Gear Mesh (Out-of-Mesh Air Stream)		20°
33	Input Pinion Tooth Root		

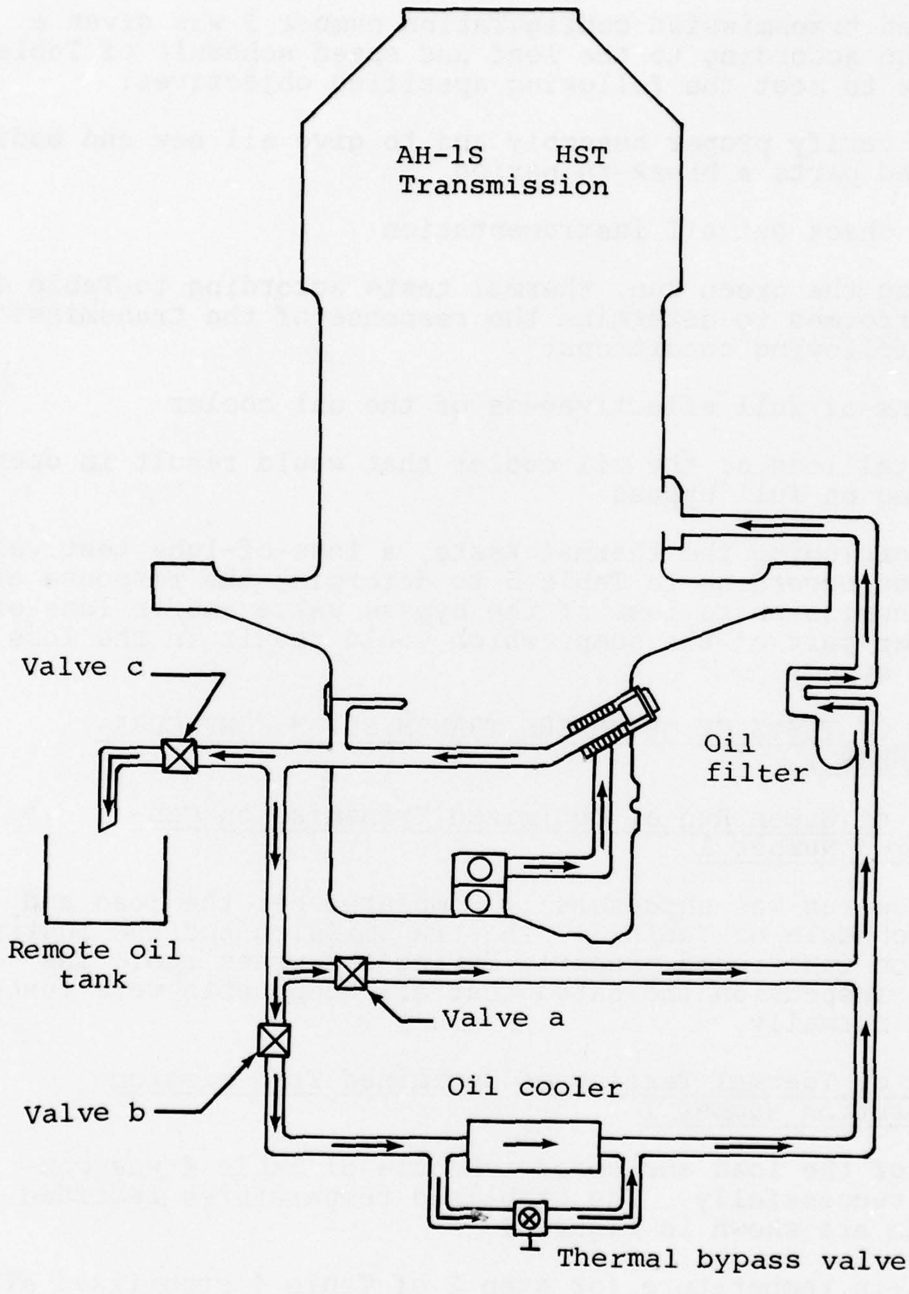


Figure 3. Schematic of oil cooler bypass and transmission drainage system.

Description of Tests of Optimized Transmission Configuration Number 1

Optimized transmission configuration number 1 was given a green run according to the load and speed schedule of Table 3 in order to meet the following specified objectives:

- To verify proper assembly and to give all new and modified parts a break-in period
- To check out all instrumentation

Following the green run, thermal tests according to Table 4 were performed to determine the response of the transmission to the following conditions:

- Loss of full effectiveness of the oil cooler
- Total loss of the oil cooler that would result in operating on full bypass

After concluding the thermal tests, a loss-of-lube test was conducted according to Table 5 to determine the response of the transmission to loss of the bypass valve and/or loss of the lower part of the sump, which would result in the loss of the oil supply.

RESULTS OF TESTS OF OPTIMIZED TRANSMISSION CONFIGURATION NUMBER 1

Results of Green Run of Optimized Transmission Configuration Number 1

The green run was successfully completed per the load and speed schedule of Table 3. The transmission and the instrumentation functioned properly during the green run. The postrun inspection indicated that all components were functioning normally.

Results of Thermal Testing of Optimized Transmission Configuration Number 1

Step 1 of the load and speed schedule of Table 4 was completed successfully. The stablized temperatures recorded for this run are shown in Figure 4.

The oil-in temperature for step 2 of Table 4 stabilized at 279°F with the oil cooler on full bypass. The 260° ±10°F oil-in temperature specified for step 2 of Table 4 was slightly

TABLE 3. 2.8 HOUR RUN-IN CYCLE

STEP NO.	HOURS TO RUN	ACCUM TIME (hours)	MAIN XMSN INPUT (rpm)	HORSE-POWER APPROX.	OUTPUT (rpm)	ACTUAL MAST TORQUE (in.-lb)	MAST TORQUE VALUE (%)	ACTUAL TAIL ROTOR OUTPUT (rpm)	TORQUE TAIL ROTOR OUTPUT (in.-lb)
1	.1		4000	Min.	196	Min.	--	2608	Min.
2	.1		4450	88	218	25534	17.02	2901	350
3	.1		4900	97	241	25534	17.02	3194	350
4	.1		5350	106	263	25534	17.02	3488	350
5	.1	0.5	5800	115	285	25534	17.02	3781	350
6	.2		5800	284	285	63084	42.06	3781	600
7	.2		6200	470	304	87116	58.08	4042	700
8	.2		6600	571	324	111148	74.10	4303	800
9	.2	1.3	7040	740	346	135180	90.12	4590	900
10	.1		5800	897	285	198362	132.22	3781	1250
11	.1		6000	929	295	198475	132.30	3911	1498
12	.1		6200	961	304	199233	132.80	4042	1793
13	.1		6400	1065	314	213763	142.49	4172	2039
14	.1		6400	1065	314	213763	142.49	4172	1510
15	.1		6400	1065	314	213763	142.49	4172	2341
16	.1		6400	1092	314	219218	146.13	4172	1133
17	.1		6400	1062	314	213160	142.09	4172	2643
18	.1		6400	1062	314	213160	142.09	4172	1133
19	.1		6400	1030	314	206738	137.81	4172	3021
20	.1		6600	1175	324	228562	152.35	4303	1098
21	.1		6600	1030	324	200357	133.55	4303	3222
22	.1		6600	1175	324	228562	152.35	4303	1098
23	2 Min.		6600	1000	324	194521	129.66	4303	3515
24	3 Min.		6600	1000	324	194521	129.66	4303	1098
25	2 Min.		6600	1000	324	194521	129.66	4303	3515
26	3 Min.		6600	1000	324	194521	129.66	4303	1098
27	2 Min.		6600	1000	324	194521	129.66	4303	3515

TABLE 4. THERMAL BASELINE TESTING LOAD AND SPEED SCHEDULE

STEP	RUN TIME (hr)	XMSN INPUT		MAIN ROTOR MAST				TAIL ROTOR MAST		OIL-IN TEMP (°F) (2)
		RPM	HORSE-POWER (1)	TORQUE (in.-lb)	HORSE-POWER	LIFT LOAD (lb)	SHEAR LOAD (lb)	TORQUE (in.-lb)	HORSE-POWER	
1	(3)	6600	950	176042	905	7200	575	1143	30	200 ± 5
2	(3)	6600	950	176042	905	7200	575	1143	30	260 ± 10
3	(4)	6600	950	176042	905	7200	575	1143	30	--

(1) This value includes 1.6% of the transmitted main rotor and tail rotor horsepower.

(2) These are stabilized temperatures where stabilized is defined as 1°F or less change in 0.1 hour.

(3) Run until the specified stabilized temperature is attained.

(4) Run with the oil cooler bypassed until the oil-in temperature stabilizes or until the temperature of the hottest monitored component reaches 400°F.

TABLE 5. LOSS-OF-LUBE TEST LOAD AND SPEED SCHEDULE

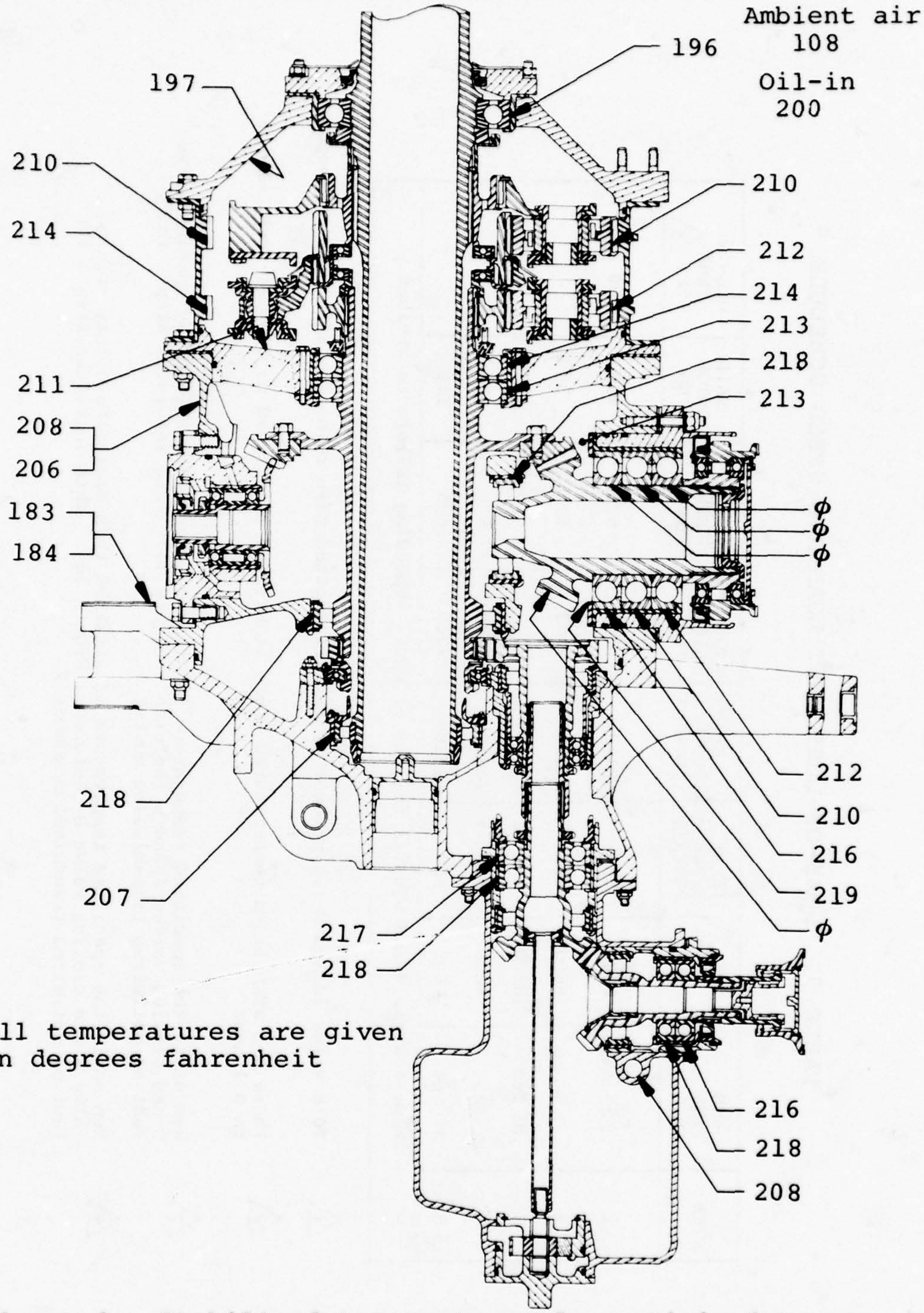
STEP	RUN TIME (hr)	XMSN	INPUT	MAIN ROTOR MAST			TAIL ROTOR hp	OIL-IN TEMP (°F) 2
		RPM	HORSE POWER 1	TORQUE (in.-lb)	LIFT (lb)	SHEAR (lb)		
1	3 4	6600	680	124299	7200	575	30	230 ± 10
2	.5	6600	680	124299	7200	575	30	
3	30 Sec	6600	680	124299	7200	575	110	
4	.2	6600	680	124299	7200	575	30	
5	30 Sec	6600	680	124299	7200	575	110	
-	Repeat Steps 4 and 5 until failure or until impending failure is obvious.							

1 This value includes 1.6 percent of the transmitted main rotor and tail rotor horsepower.

2 These are stabilized temperatures where stabilized is defined as 1°F, or less, change in 0.1 hour.

3 Run until the specified temperature is attained then drain the oil by opening valve C and closing valves A and B (Reference Figure 3). This initiates Step 2 for test of optimized transmission number 1.

4 Run until the specified temperature is attained then drain the oil by opening valve A and closing valve B (Reference Figure 38). This initiates Step 2 for test of optimized transmission number 2.



All temperatures are given in degrees fahrenheit

Figure 4. Stabilized temperatures for optimized transmission configuration number 1 at 200°F oil-in, 950 horsepower (Step 1 of Table 4).

exceeded due to the difficulty of stabilizing the oil temperature at this step. The stabilized temperatures recorded for this run are shown in Figure 5.

Step 3 of Table 4 was run with the oil cooler completely bypassed using a short, direct oil line from the oil outlet of the transmission to the oil inlet. This simulates total loss of the oil cooler. The stabilized temperatures for this run are shown in Figure 6.

Figure 7 shows a plot of the oil cooler requirements versus the oil inlet temperature for optimized transmission configuration number 1 based on the data taken during the thermal running.

Results of Loss-of-Lube Test of Optimized Transmission Configuration Number 1

The loss-of-lube test of optimized transmission configuration number 1 was performed according to the load and speed schedule of Table 5. The test transmission was operated at 680 input horsepower (60 percent of MCP) under normal lubrication conditions until the inlet oil temperature stabilized at 224°F. Then, with the transmission still operating at 680 input horsepower (30 hp through the tail rotor, lift and bending loads applied to the main rotor mast), valve C was opened and valves A and B were closed (reference Figure 3), forcing the oil to be pumped from the transmission. After complete loss of the main oil supply, this transmission continued to operate for 25 minutes before torque was lost due to a failure of the lower planetary stage. Figure 8 shows transmission temperatures at failure. Figure 9 is a plot of the lower planetary ring gear temperatures recorded during the loss-of-lube test. At failure, the ring gear temperature was 827°F. Figures 10 through 16 show temperature plots of various components during the 25-minute loss-of-lube test.

Disassembly of the transmission following the 25-minute loss-of-lube test revealed that this failure was very similar to the planetary failures previously reported under this contract (Reference 2). Figures 17 through 35 show various components following the loss-of-lube test of optimized transmission configuration number 1. The teeth had softened and were flattened or stripped from all four of the lower planetary pinions. All of the lower planetary pinions were oblong and deformed. One of the pinions was broken and all the rollers and the bearing cage were missing from the planetary pinion. Some of the rollers retained within the other three lower planetary pinions were skewed sideways. The tangs that retain these rollers had broken off of the bearing cage.

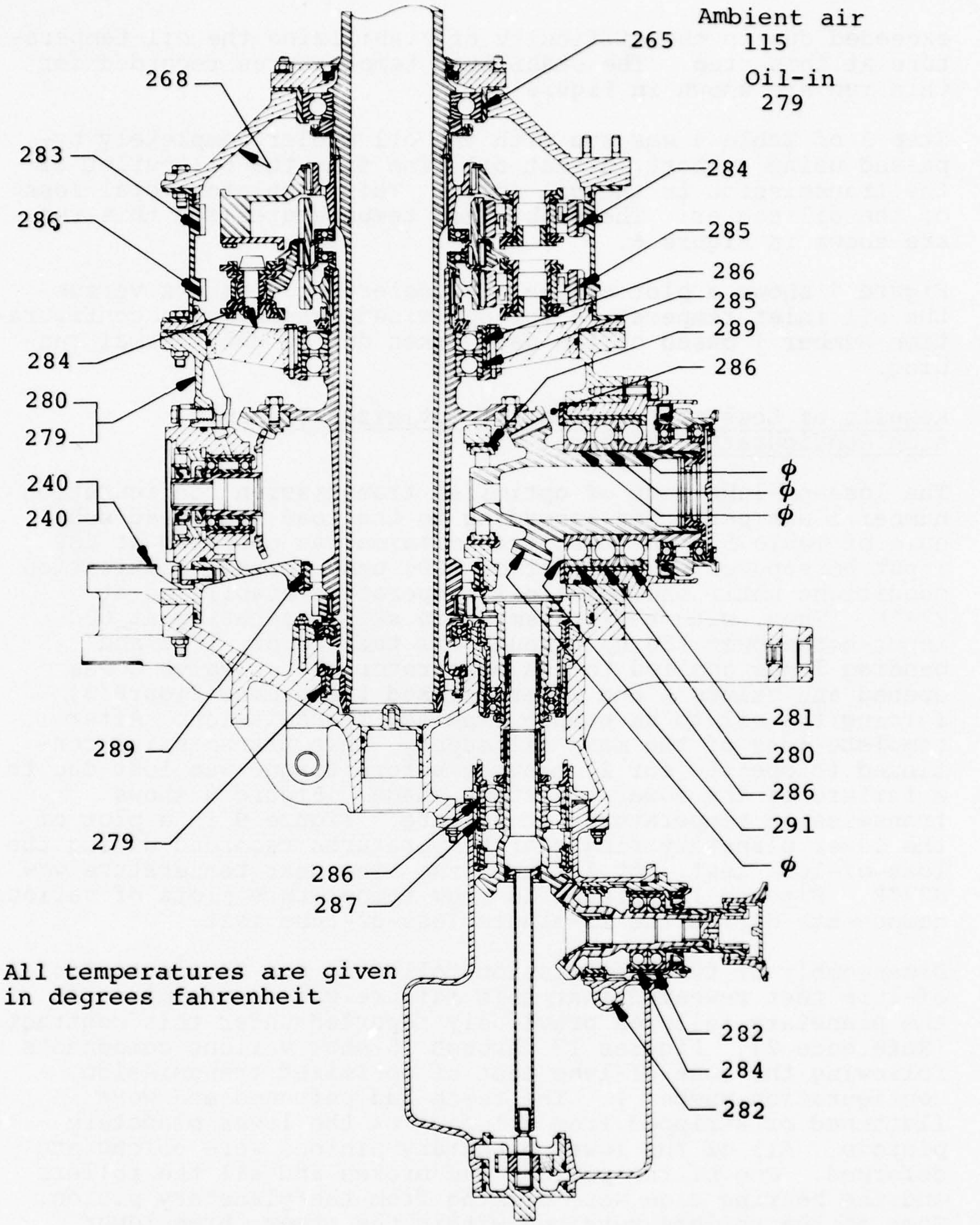


Figure 5. Stabilized temperatures for optimized transmission configuration number 1 at 279°F oil-in, 950 horsepower (Step 2 of Table 4).

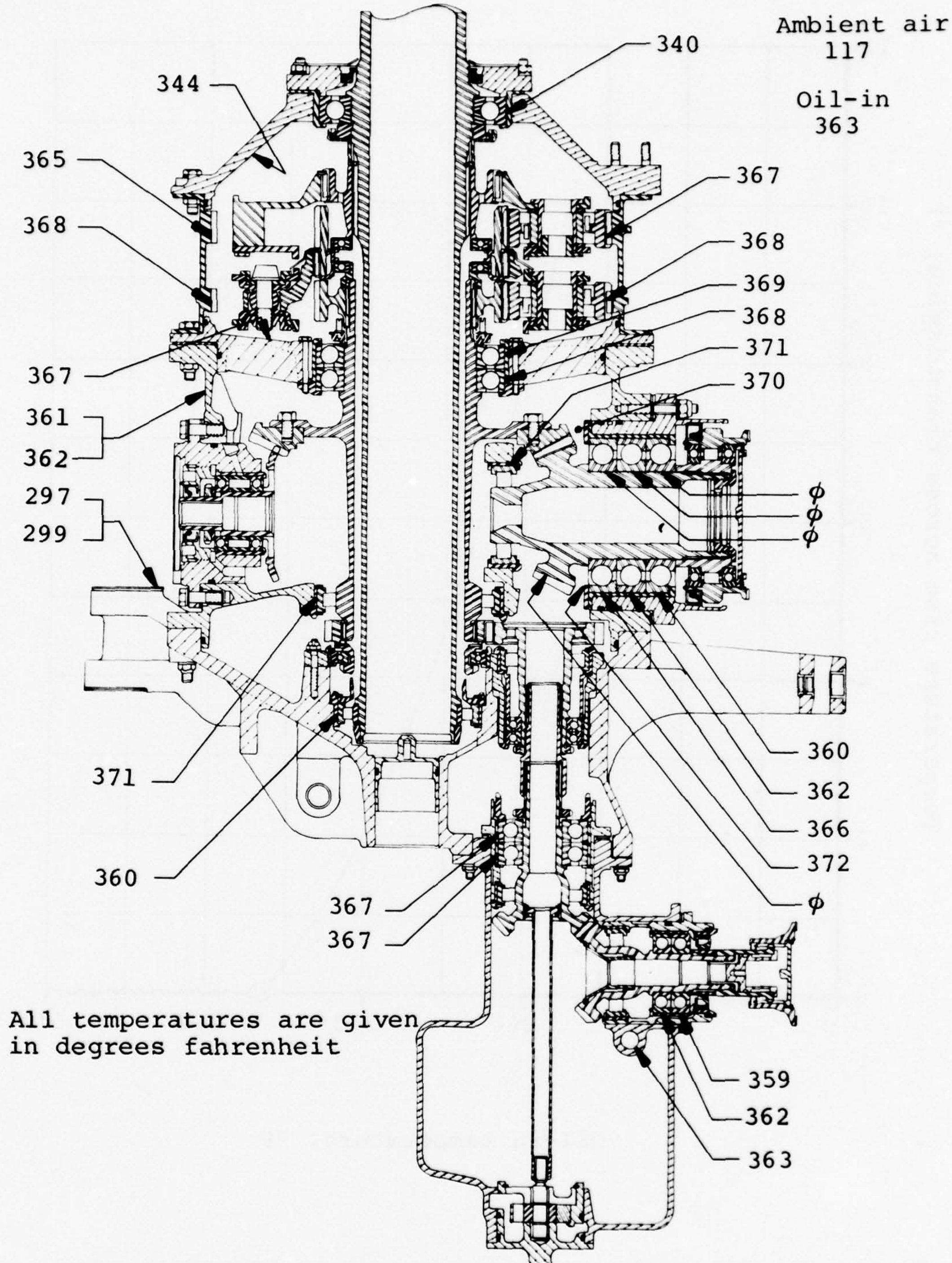


Figure 6. Stabilized temperatures for optimized transmission configuration number 1 at 363°F oil-in, 950 horsepower (Step 3 of Table 4).

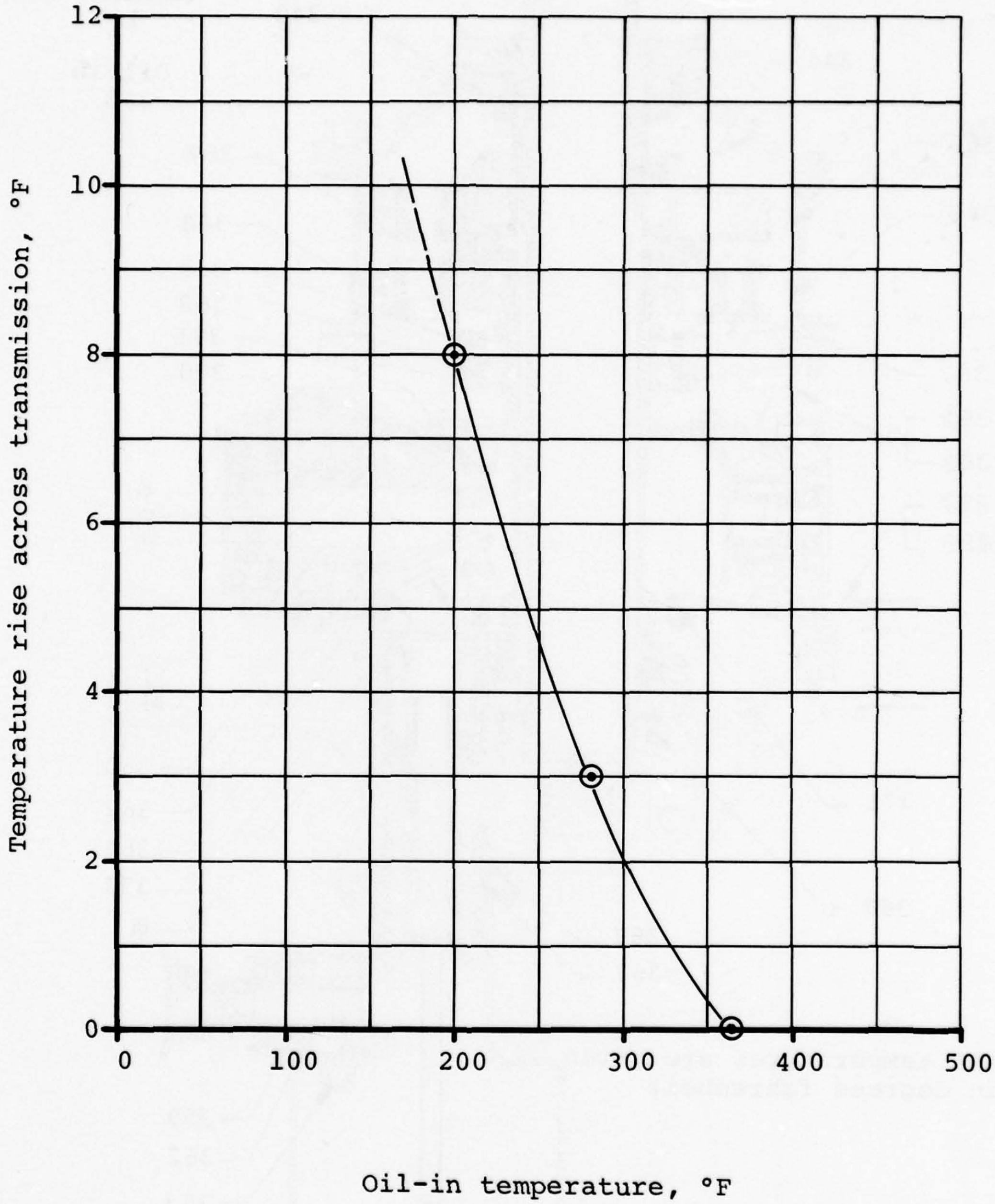


Figure 7. Oil cooler requirements of AH-1S HST at 950 horsepower.

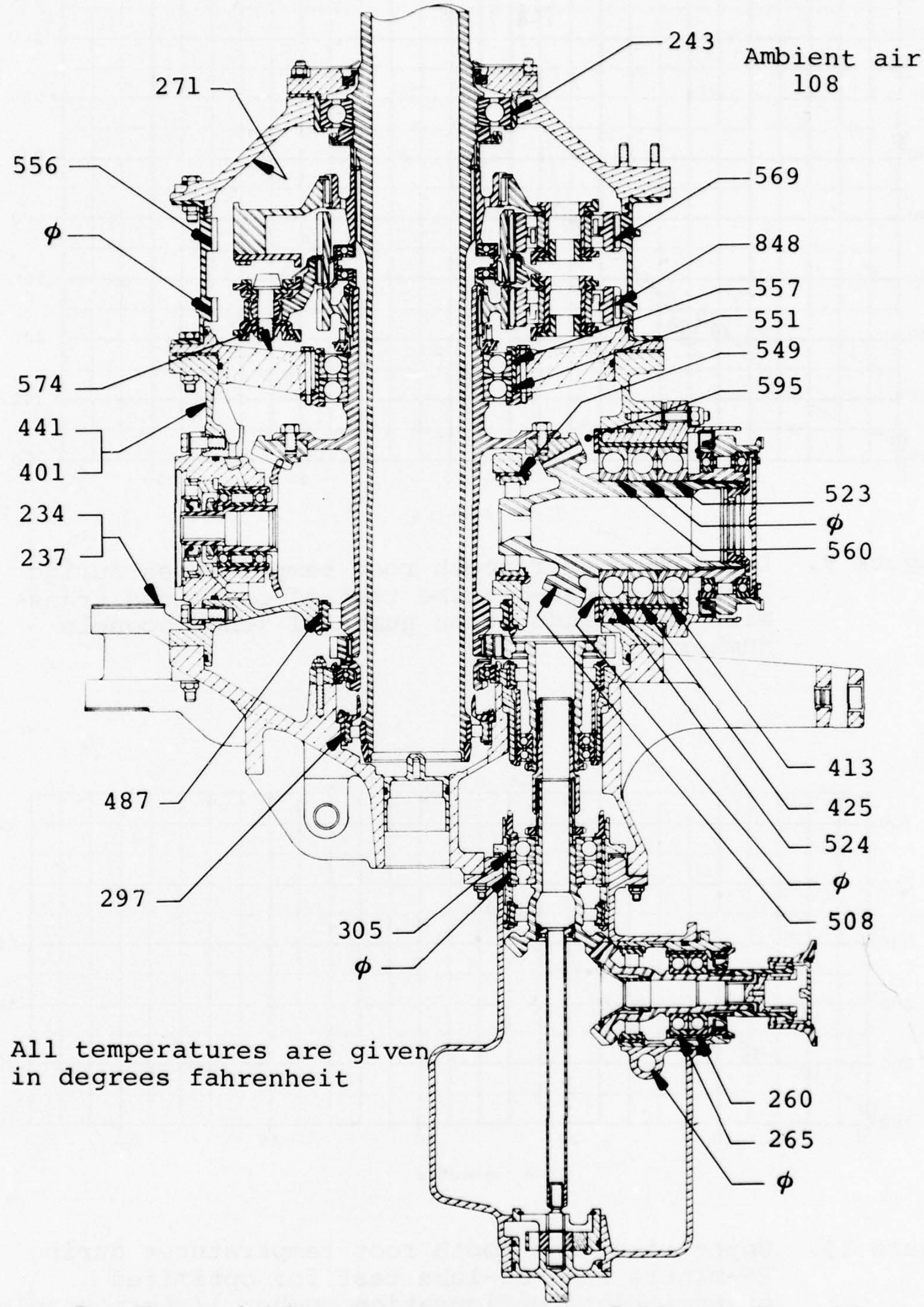


Figure 8. Transmission temperatures at failure after 25-minute loss-of-lube test of optimized transmission configuration.

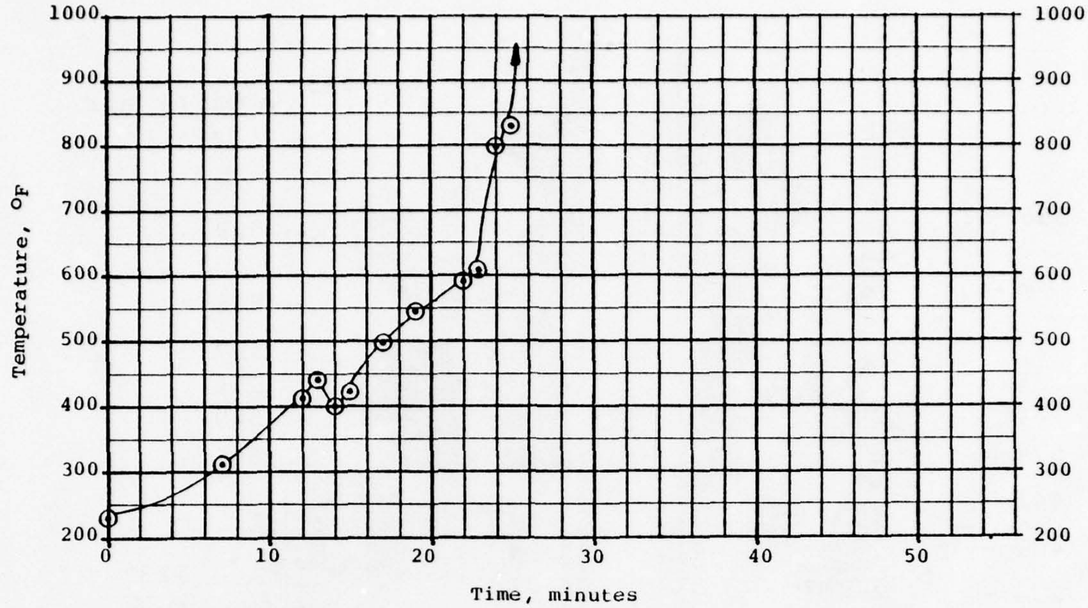


Figure 9. Lower ring gear tooth root temperatures during 25-minute loss-of-lube test of optimized transmission configuration number 1 (thermocouple number 13).

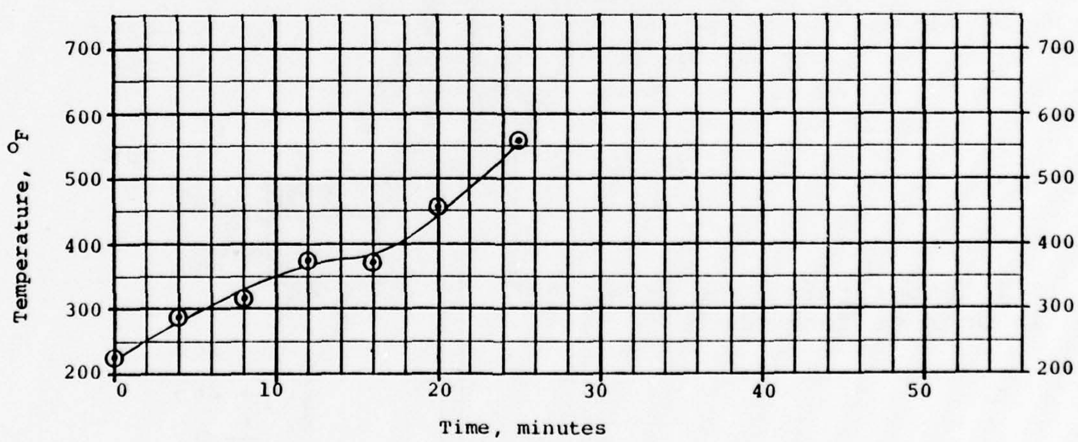


Figure 10. Upper ring gear tooth root temperatures during 25-minute loss-of-lube test for optimized transmission configuration number 1(thermocouple number 12).

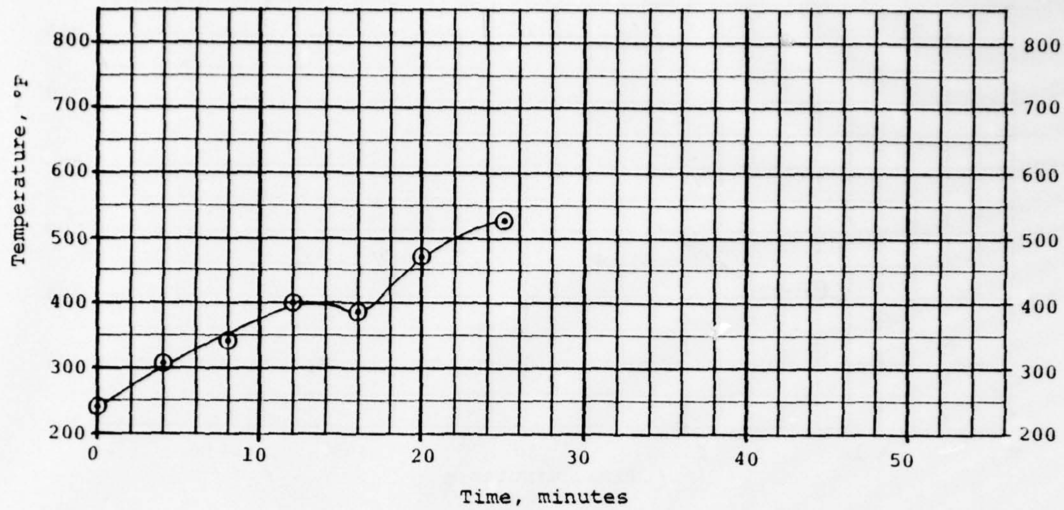


Figure 11. Inboard triplex bearing outer race temperatures during 25-minute loss-of-lube test for optimized transmission configuration number 1 (thermocouple number 18).

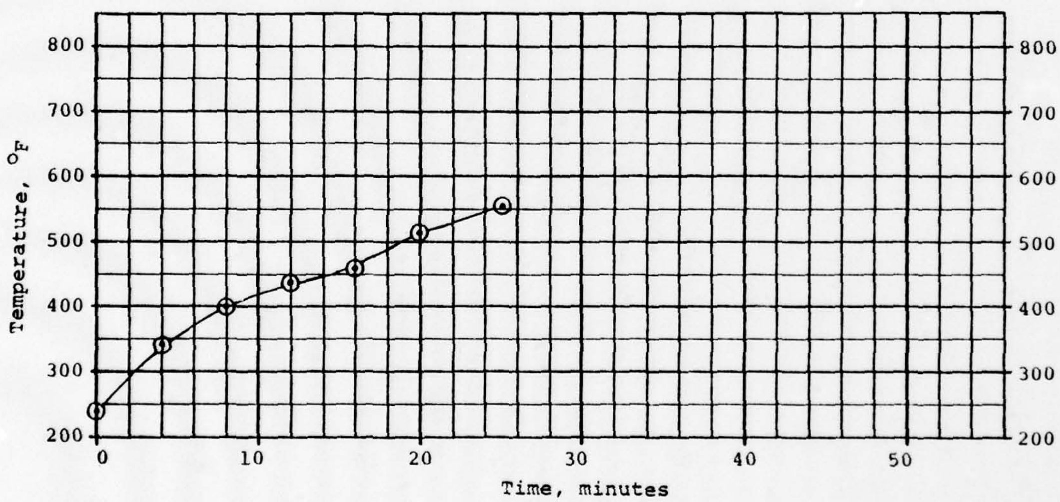


Figure 12. Inboard triplex bearing inner race temperatures during 25-minute loss-of-lube test for optimized transmission configuration number 1 (thermocouple number 21).

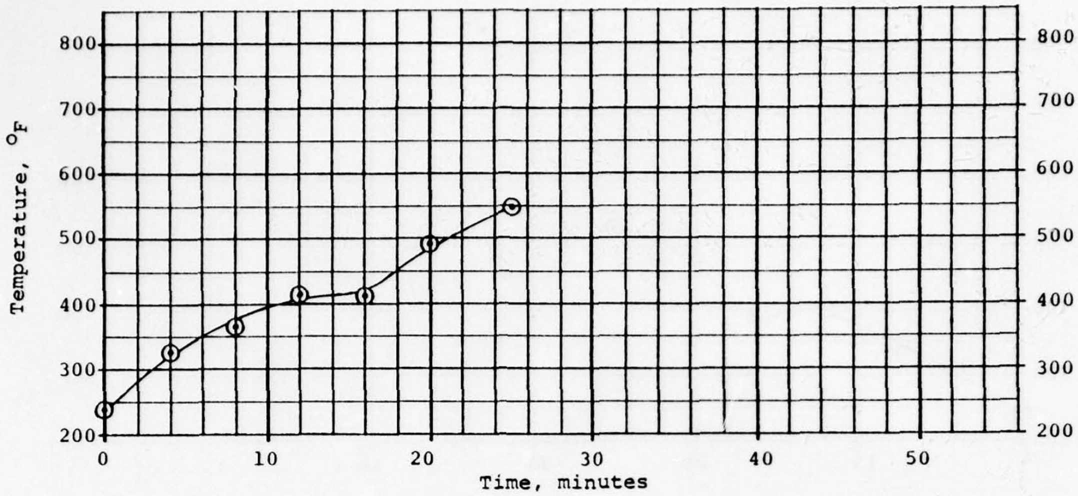


Figure 13. Input pinion roller bearing temperatures during 25-minute loss-of-lube test for optimized transmission configuration number 1 (thermocouple number 5).

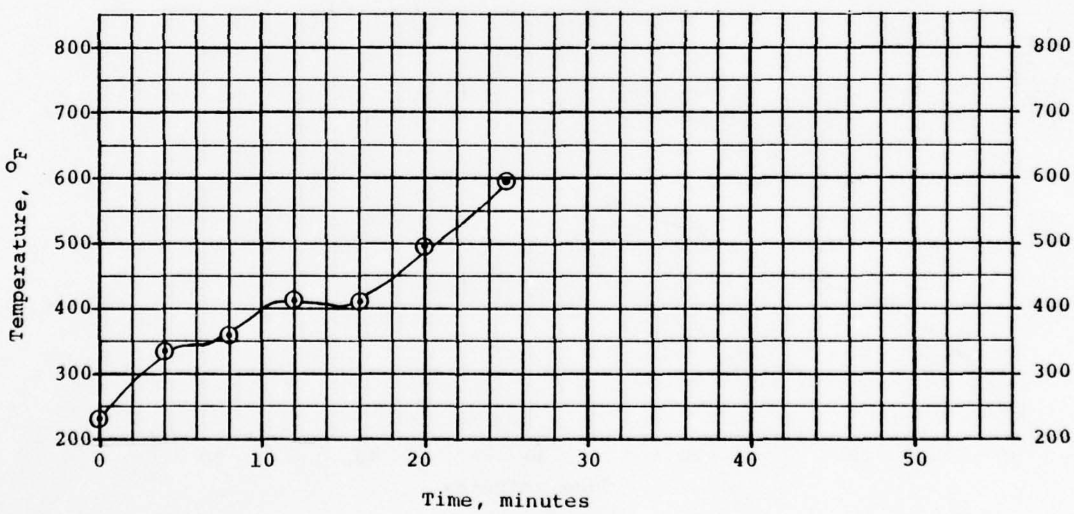


Figure 14. Input bevel gear set out-of-mesh airstream temperatures during 25-minute loss-of-lube test for optimized transmission configuration number 1 (thermocouple number 32).

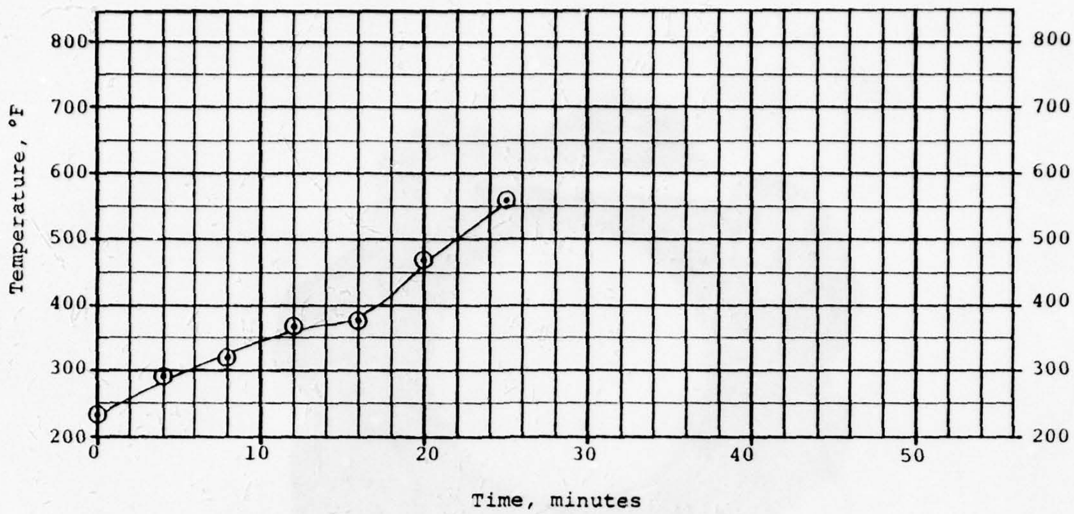


Figure 15. Gearshaft duplex bearing outer race temperatures during 25-minute loss-of-lube test for optimized transmission configuration number 1 (thermocouple number 3).

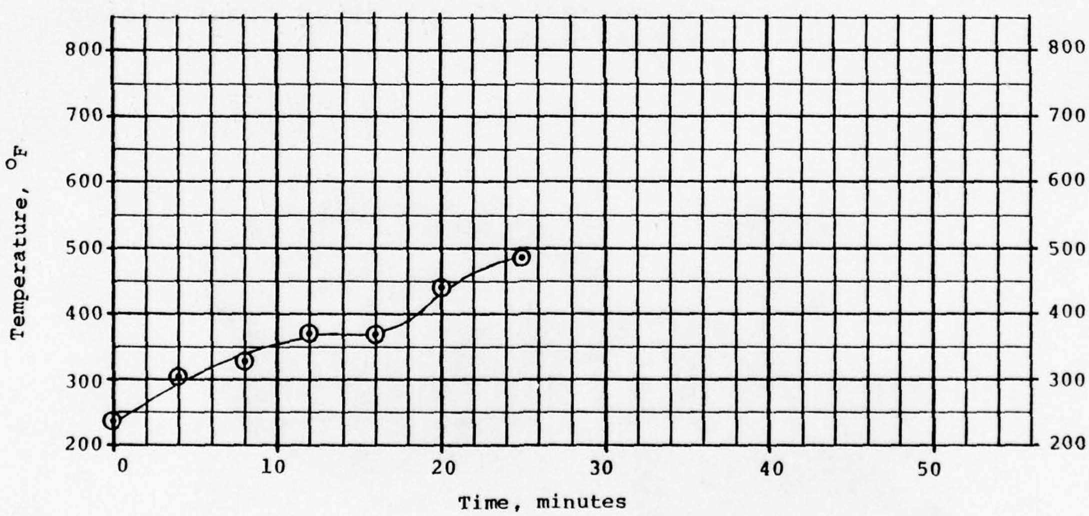


Figure 16. Gearshaft roller bearing outer race temperatures during 25-minute loss-of-lube test for optimized transmission configuration number 1 (thermocouple number 6).

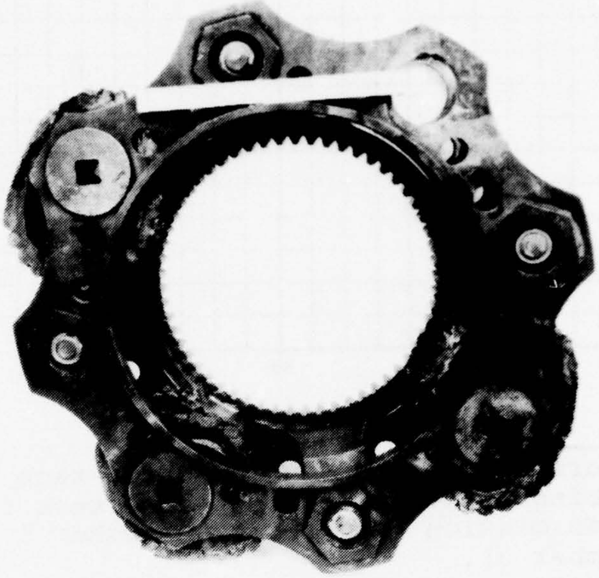


Figure 17. Lower planetary assembly after 25-minute loss-of-lube test of optimized transmission configuration number 1.

Figure 18. Lower planetary pinion, bearing inner race, roller, roller guides, and retainer after 25-minute loss-of-lube test of optimized transmission configuration number 1.

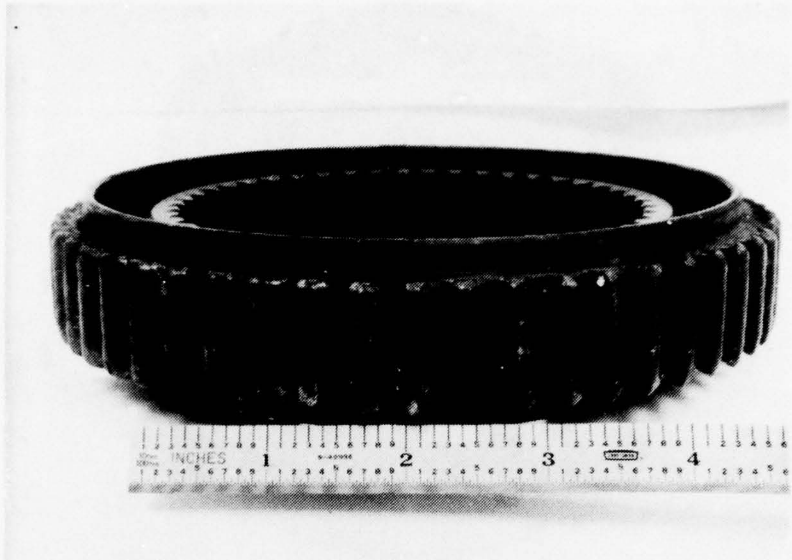


Figure 19. Lower sun gear after 25-minute loss-of-lube test of optimized transmission configuration number 1.

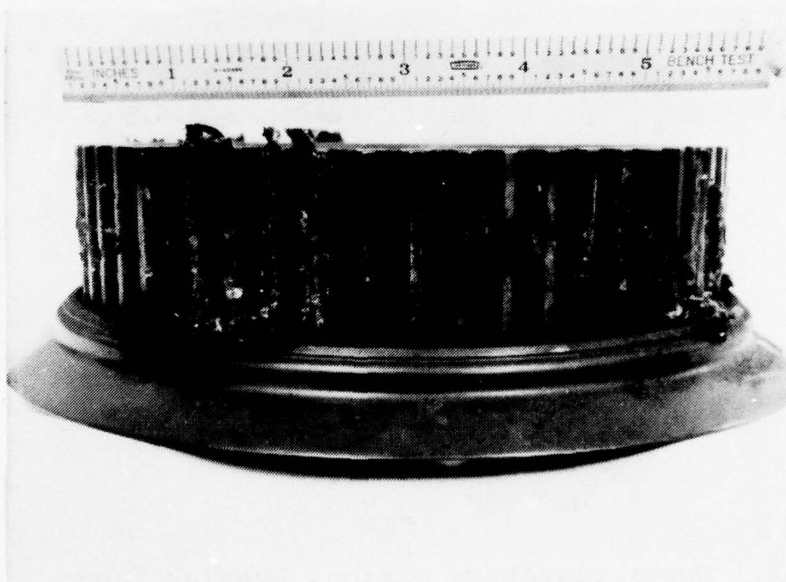


Figure 20. Upper sun gear after 25-minute loss-of-lube test of optimized transmission configuration number 1.

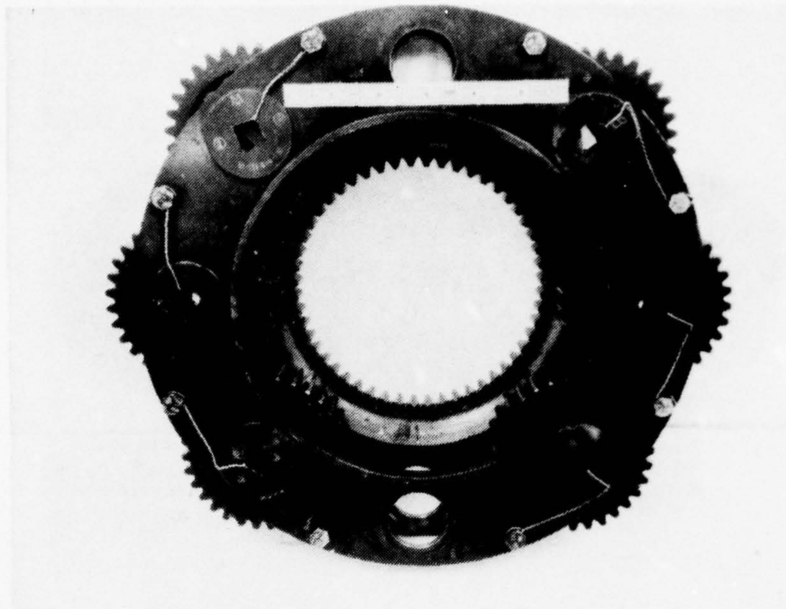


Figure 21. Upper planetary assembly after 25-minute loss-of-lube test for optimized transmission configuration number 1.

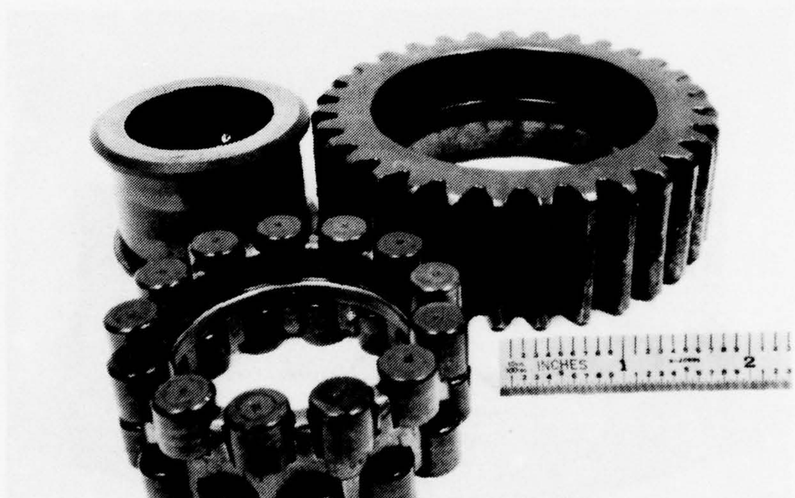


Figure 22. Upper planetary pinion, bearing inner race, rollers, roller guides, and retainer after 25-minute loss-of-lube test of optimized transmission configuration number 1.

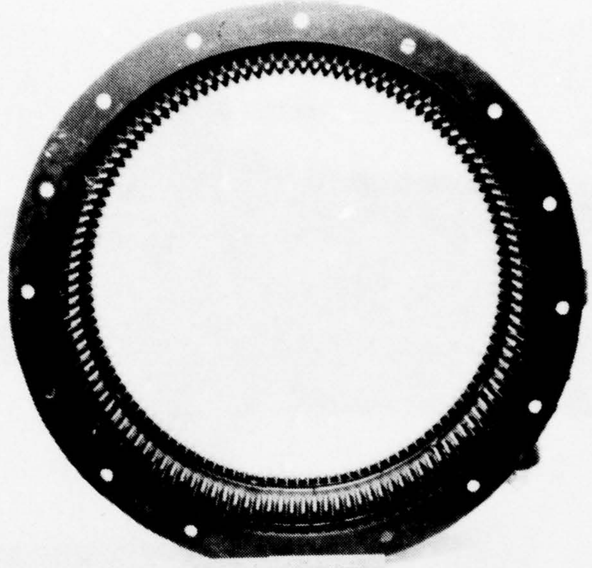


Figure 23. Ring gear case after 25-minute loss-of-lube test of optimized transmission configuration number 1.

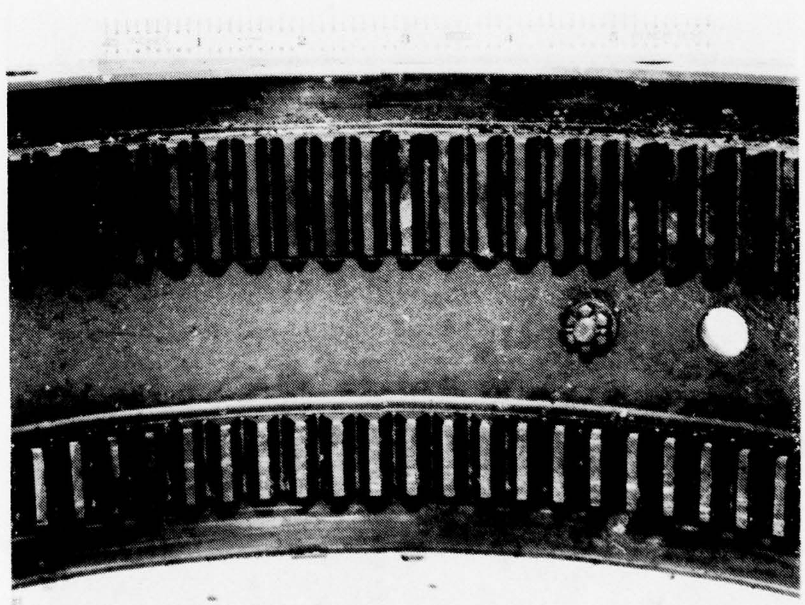


Figure 24. Upper ring gear teeth (top) and lower ring gear teeth (bottom) after 25-minute loss-of-lube test of optimized transmission configuration number 1.

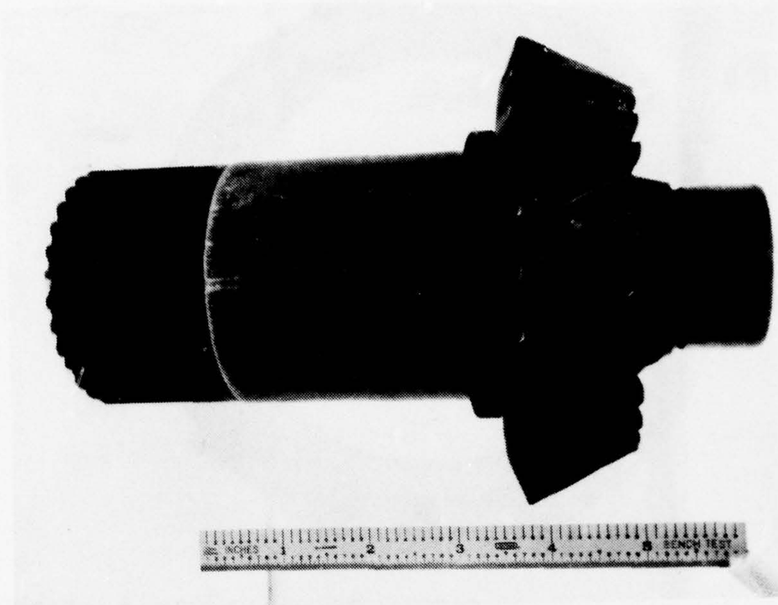


Figure 25. Main input pinion after 25-minute loss-of-lube test of optimized transmission configuration number 1.

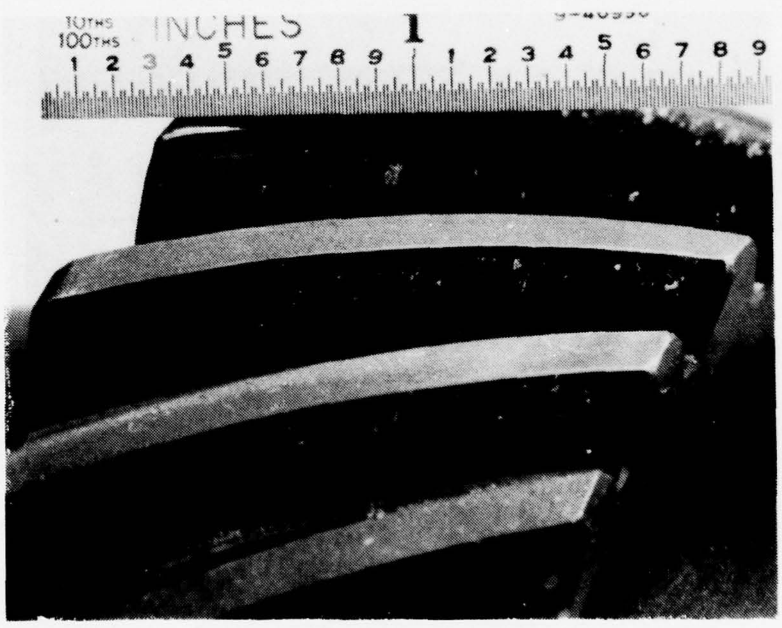


Figure 26. Main input pinion teeth (drive side) showing light scoring after 25-minute loss-of-lube test of optimized transmission configuration number 1.

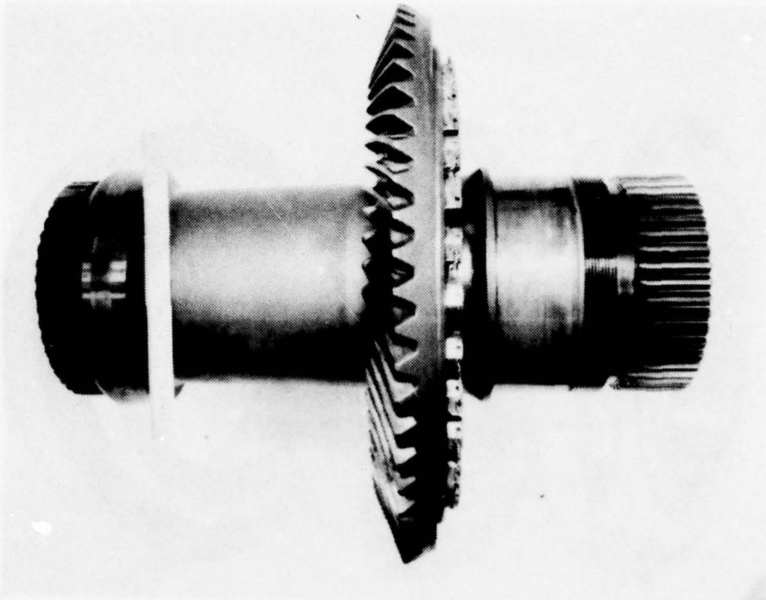


Figure 27. Main input gear and gearshaft after 25-minute loss-of-lube test of optimized transmission configuration number 1.

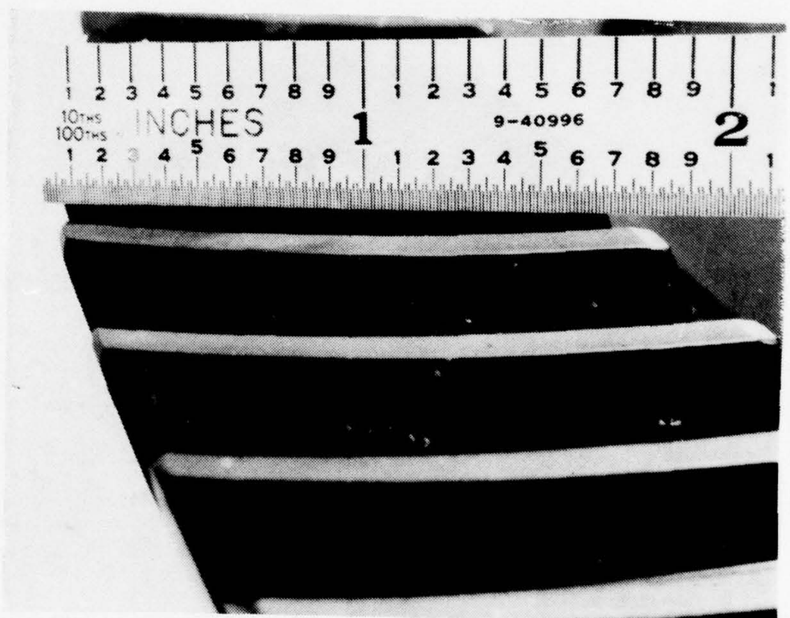


Figure 28. Main input gear teeth (drive side) showing light scoring after 25-minute loss-of-lube test of optimized transmission configuration number 1.

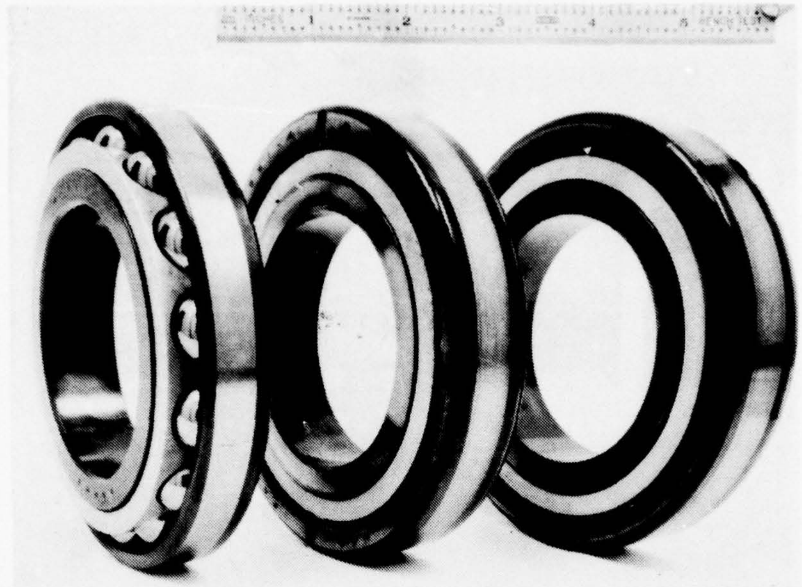


Figure 29. Main input triplex bearing after 25-minute loss-of-lube test of optimized transmission configuration number 1.

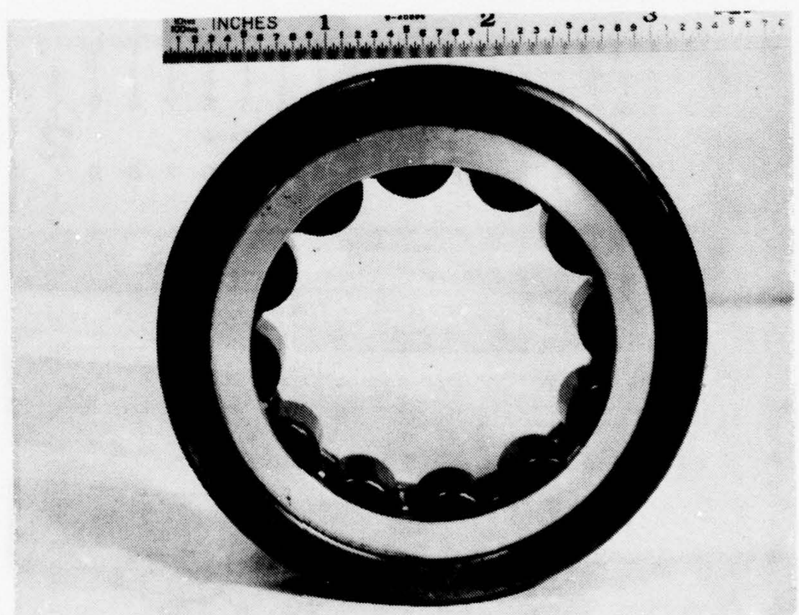


Figure 30. Main input pinion roller bearing after 25-minute loss-of-lube test of optimized transmission configuration number 1.

Figure 31. Main gearshaft duplex bearing after 25-minute loss-of-lube test of optimized transmission configuration number 1.

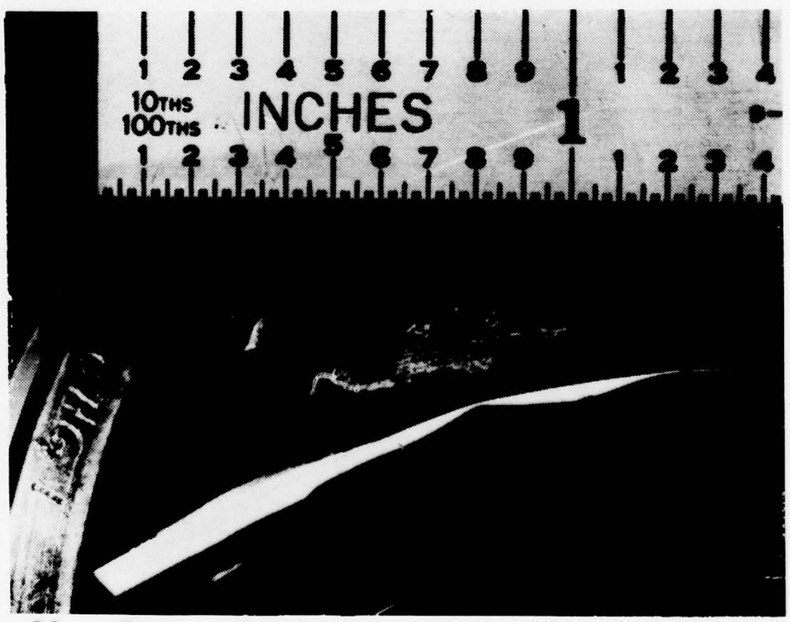


Figure 32. Sump output gear teeth (drive side) showing light scoring after 25-minute loss-of-lube test of optimized transmission configuration number 1.

Figure 33. Fan accessory drive duplex bearing after 25-minute loss-of-lube test of optimized transmission configuration number 1.

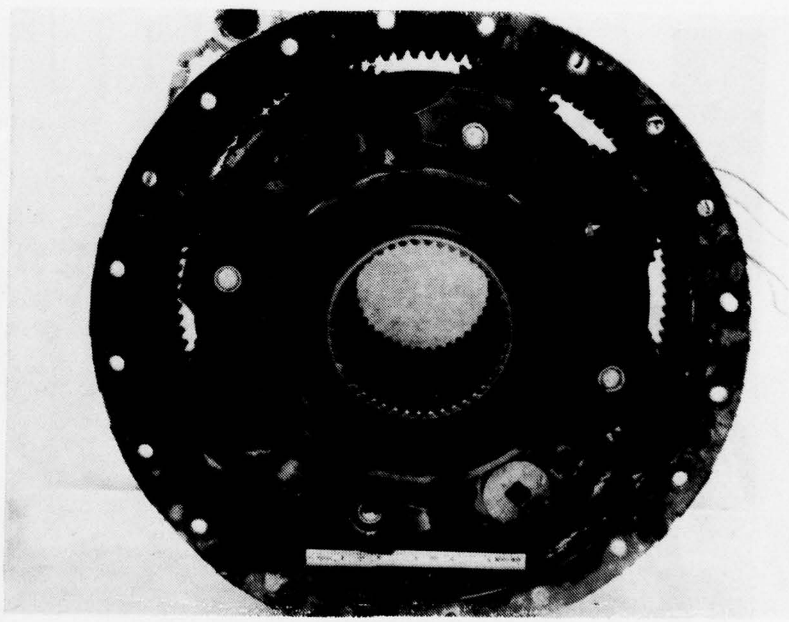


Figure 34. View looking into ring gear case after 25-minute loss-of-lube test of optimized transmission configuration number 1.

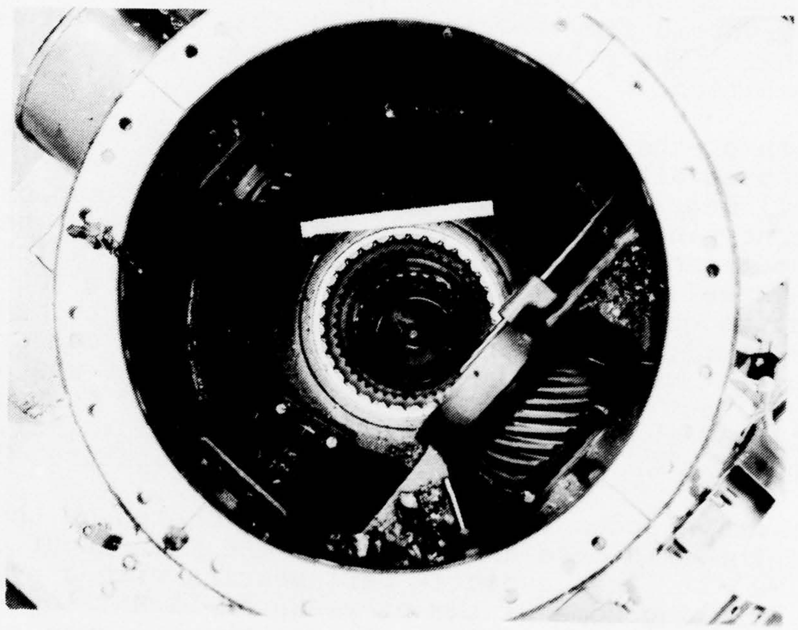


Figure 35. View looking into main and support cases after 25-minute loss-of-lube test of optimized transmission configuration number 1.

Debris in the form of chewed-up and misshapen rollers and pieces of bearing retainers were strewn throughout the transmission. The lower planetary sun gear teeth had softened and were beginning to roll over. Both the sun gear and the planetary pinions are carburized gears. The lower ring gear, which is nitrided, had some chipped teeth and had been damaged by debris, but there was no indication that the ring gear teeth had softened.

The upper planetary was dry and had been damaged extensively by debris from the lower planetary, but it was still capable of continuing operation. The roller bearings were contaminated by debris from the lower planetary stage but were still functional. The bronze bearing retainers appeared to be in good condition.

The teeth of the main input spiral bevel gear set were moderately scored after the 25-minute loss-of-lube run. The triplex ball bearing and the roller bearing that support the main input pinion still had slight traces of oil when removed from the transmission. The balls and rollers (which are made of M-50 steel) had a bluish tint as a result of the high temperature operation, but the bearings still turned smoothly and, seemingly, suffered no real damage. The duplex ball bearing that supports the main input gearshaft was still functional but had suffered debris damage and turned roughly. The balls of the duplex bearing (made of M-50 steel) also had a bluish tint as a result of the high temperature operation.

The fan drive accessory quill that is located on the forward side of the main case and driven by the main input gear (204-040-701-1) utilizes a duplex ball bearing with a nylatron retainer. During some of the previous AH-1S HST loss-of-lube tests conducted under this contract, the nylatron retainer of the inboard bearing of this duplex bearing had melted. However, both of the nylatron retainers in the duplex pair from loss-of-lube test of transmission number 1 remained whole and were still operational at the end of the test.

The tail rotor drive spiral bevel gear set located in the sump area was scored slightly. Both gears and bearings were still oily in the sump area and, aside from the slightly-scored condition of the gear set, no other damage was apparent.

DISCUSSION OF RESULTS OF OPTIMIZED TRANSMISSION CONFIGURATION NUMBER 1 TESTING

The temperature for the lower planetary assembly during the 25-minute loss-of-lube test increased at a much faster rate than was expected. Prior to this loss-of-lube test, BHT had conducted exploratory tests on an AH-1S transmission modified to the Test 1 configuration. Two of the exploratory tests were conducted at 60 percent MCP, which is the same power level as for test number 1 but they were not run to failure. Figure 36 is a comparison of the lower ring gear tooth root temperatures for the exploratory tests and for the optimized configuration loss-of-lube test number 1. The rate of temperature rise for the optimized configuration loss-of-lube test during the first fifteen minutes of operation is much greater than the rate of temperature rise for exploratory test 1B. The temperature plot for the lower ring gear teeth on optimized configuration loss-of-lube test number 1 tends to follow the plots obtained from the loss-of-lube tests conducted at 84 percent MCP. Figure 37 shows a comparison of lower ring gear tooth root temperatures from optimized configuration loss-of-lube test number 1 versus the 19- and 21-minute loss-of-lube tests. The reason for the lower ring gear temperatures from optimized configuration loss-of-lube test number 1 following the temperature plots for the 84 percent MCP loss-of-lube instead of those for the 60 percent MCP loss-of-lube exploratory tests is not known. One possible cause might be that the transmission incurred some unknown damage during the thermal baseline running when the oil inlet temperature was allowed to stabilize at 363°F. However, no monitored transmission component exceeded 400°F and no anomalies were found during partial disassembly after the green run and thermal base run.

It was not possible to ascertain the primary mode of failure in the lower planetary stage by examining the failed components. The failure had progressed to such an extent that both gears and bearings were badly deformed and no specific causations could be positively established. The combination of high loads and high temperatures forced the failure of the lower planetary pinions. Apparently, at the high temperatures of no-lube planetary operation the planetary pinions softened and distorted under predesign heavy gear loading, causing increased heat generation at both gear meshes and in the planetary roller bearing. This led to the oblong shape of the pinions and to the failed bearings and gear teeth.

The distortion and misalignment that occurs in the lower planetary stage serves to concentrate the tooth loads on the ends of the teeth. To minimize this type of loading, a narrow face width lower sun gear with crowned teeth was used. The lower sun gear used during this test had a face width of 0.938 inch, compared to 1.450 inches of face width for the 205-040-229-1 lower sun gear that is in the standard AH-1S transmission. Since the planetary pinion face width is 1.333

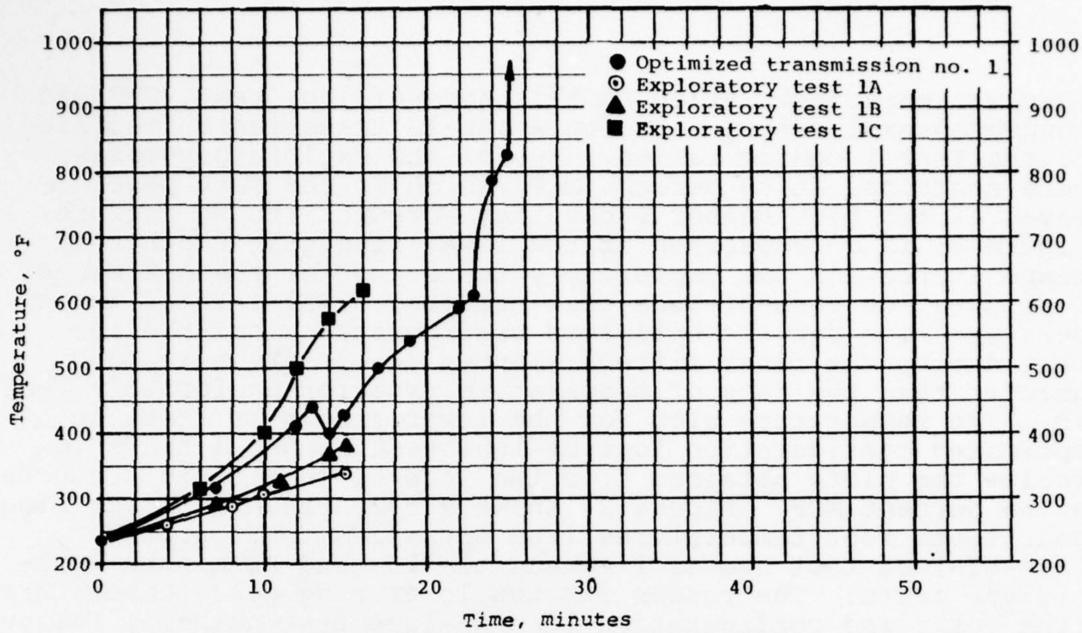


Figure 36. Comparison of lower ring gear tooth root temperatures during loss-of-lube exploratory tests and 25-minute loss-of-lube test of optimized transmission configuration number 1.

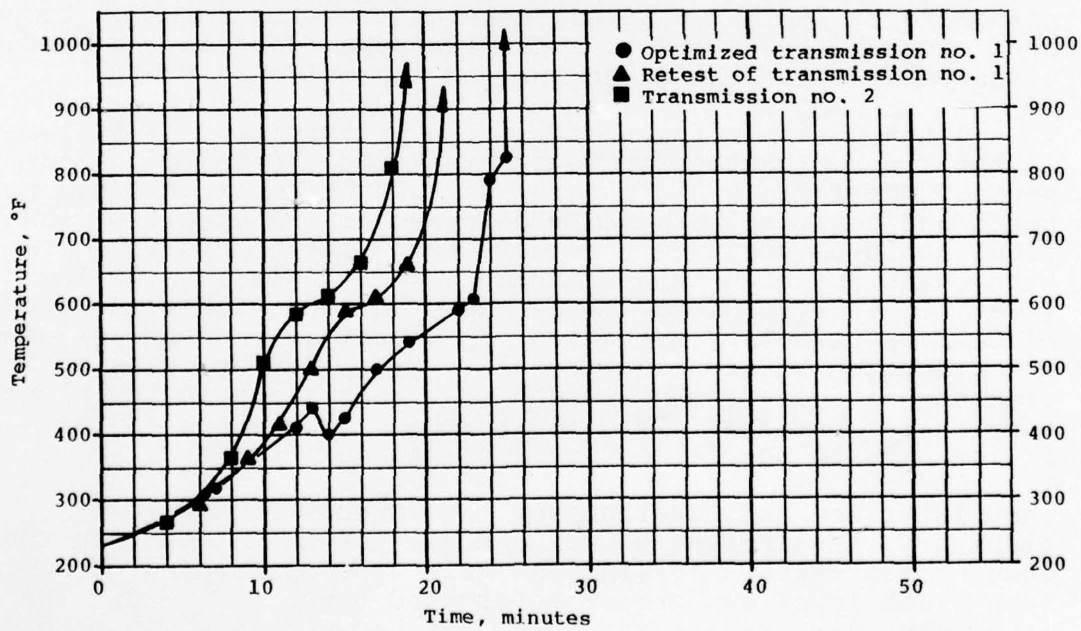


Figure 37. Comparison of lower ring gear tooth root temperatures during 25-minute loss-of-lube test of optimized transmission configuration number 1, 21-minute loss-of-lube retest of transmission number 1, and 19-minute loss-of-lube test of transmission number 2.

inches, the narrow sun gear does not engage the full face width of the planetary pinion. The face width of the lower ring gear teeth is 0.800 inch. Thus, with the narrow sun gear installed, the planetary pinion teeth have about 0.2 inch of face width per side, not contacting either the sun gear teeth or the ring gear teeth. It had been hoped that these unloaded areas would help the pinions maintain their shape during loss-of-lube operation and that use of the narrow sun gear would force the failure mode to be the stripping of the lower sun gear teeth, which is a less severe failure mode since it allows the main rotor mast to continue rotation. The failure mode in the lower planetary stage for the loss-of-lube test of optimized transmission configuration number 1, however, was the distortion of the planetary pinions.

AH-1S HST TESTING OF OPTIMIZED TRANSMISSION CONFIGURATION NUMBER 2

GENERAL OBJECTIVE

The general objective of the test of optimized transmission configuration number 2 was to determine the response of the modified AH-1S transmission operating at an optimum power level (60 percent MCP) after the complete loss of the oil supply.

TEST OF OPTIMIZED TRANSMISSION CONFIGURATION NUMBER 2

Transmission Number 2 Configuration

As defined in Table 1, the configuration for transmission number 2 was the same as for the optimized transmission configuration number 1, except that roller guides made of CVEM M-50 steel were installed in both planetaries, planetary rollers made of CVEM M-50 steel were installed in the lower planetary, and oil collectors were installed between the planetaries and above the upper planetaries. The top case was modified to attach the upper oil collector and an oil jet was modified to spray an oil stream into the upper oil collector.

The lower oil collectors consist of three pieces that are installed between the upper and lower planetaries. The collectors are attached to the ring gear case by use of the existing bolts at the three oil jet locations. Felt was bonded to the side of the collector against the ring gear case. The felt serves as an oil wick and might divert some of the oil running down the case wall into the lower oil collectors. The lower oil collectors have a volume of 95 ml (0.1 quart) each. The upper oil collector, which is one piece, has a measured volume of 1160 ml (1.22 quarts).

An experiment to determine the oil collector drainage time was performed in the BHT Bench Test Facility. The upper oil collector and one lower oil collector were placed in an oven along with a quantity of oil per MIL-L-23699. The collectors and oil were heated to 160°F, 230°F, and 300°F. The oil was poured into the collectors after it had reached the desired temperature. Oil temperature was determined using a thermal probe and a thermoelectric digital meter. The setup was left in the oven during the drainage test and checked periodically. Drainage time for the lower collector that has one 0.040-inch-diameter drain hole was 37 minutes at 160°F, 17 minutes at 230°F, and 15 minutes at 300°F. Drainage time for the upper collector that has three .040-inch-diameter drain holes was 1 hour at 160°F and 30 minutes at 300°F. No time is reported for the upper collector at 230°F because the holes became partially plugged during the test. Following the drainage test, all the collectors were garnet blasted to remove any scale from the welded aluminum that might block the drain holes.

Thermocouple locations for this test were identical to those of optimized transmission configuration number 1 as defined in Table 2 and Figure 2. An oil drainage system was installed (reference Figure 38).

Description of Tests of Optimized Transmission Configuration Number 2

Transmission number 2 was given a green run according to the load and speed schedule of Table 3 in order to meet the following specified objectives:

- To verify proper assembly and to give all new and modified parts a break-in period

- To check out all instrumentation

Following the green run, a thermal baseline test was performed according to Table 6 to determine the oil cooler requirement during operation at 950 horsepower.

The loss-of-lubrication test was conducted according to Table 5 to determine the response of the transmission to loss of the bypass valve and/or loss of the lower part of the sump, which would result in the loss of the oil supply.

RESULTS OF TESTS OF OPTIMIZED TRANSMISSION CONFIGURATION NUMBER 2

Results of Green Run of Optimized Transmission Configuration Number 2

The green run was completed per the load and speed schedule of Table 3. The post green run inspection indicated that the transmission was functioning normally. The instrumentation appeared to be working properly.

Results of Thermal Testing of Optimized Transmission Configuration Number 2

The thermal testing of optimized transmission configuration number 2 was completed per the load and speed schedule of

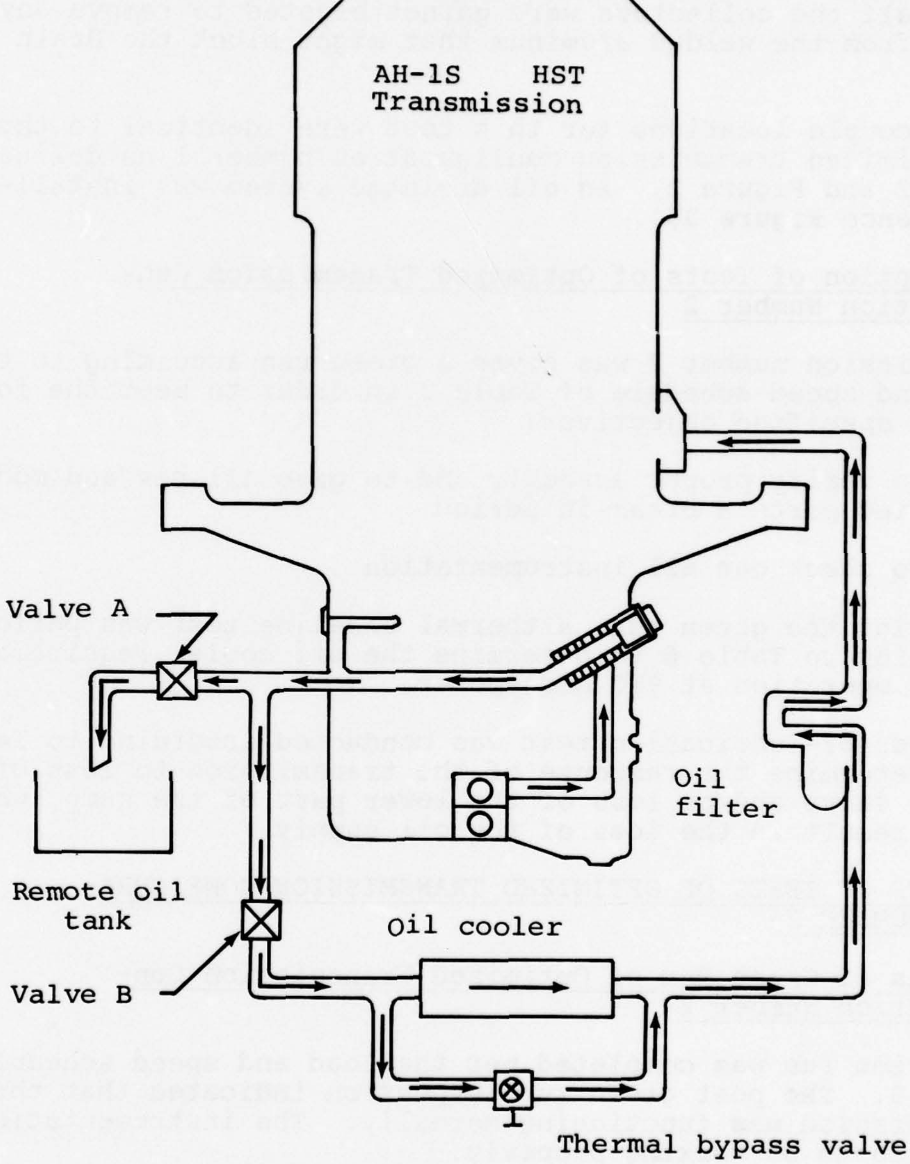


Figure 38. Schematic of transmission drainage system.

TABLE 6. THERMAL BASLINE TESTING LOAD AND SPEED SCHEDULE

STEP	RUN TIME (hr)	XMSN rpm	INPUT HP (1)	MAIN ROTOR MAST TORQUE (in.-lb)	MAIN ROTOR MAST HORSE-POWER	MAIN ROTOR MAST LIFT LOAD (lb)	MAIN ROTOR MAST SHEAR LOAD (lb)	TAIL ROTOR MAST TORQUE (in.-lb)	TAIL ROTOR MAST HORSE-POWER	OIL-IN TEMP (°F) (2)
1	(3)	6600	950	176042	905	7200	575	1143	30	200 ± 5

(1) This value includes 1.6 percent of the transmitted main rotor and tail rotor horsepower.

(2) These are stabilized temperatures where stabilized is defined as 1 degree or less change in 0.1 hour.

(3) Run until the specified stabilized temperatue is attained.

Table 6. Only one data point was obtained during the thermal baseline testing, since it was suspected that the running at high temperatures during the thermal baseline tests of optimized transmission configuration number 1 may have had an influence upon the results of the loss-of-lubrication test. The stabilized temperatures recorded for this run are shown in Figure 39. A comparison of the oil cooler requirements versus the oil inlet temperature for optimized transmission configuration number 2 versus previously tested transmissions is shown in Figure 40.

Results of Loss-of-Lube Test of Optimized Transmission Configuration Number 2

The loss-of-lube test of optimized transmission configuration number 2 was performed according to the load and speed schedule of Table 7. The test transmission was operated at 680 horsepower (60 percent of MCP) under normal lubrication conditions until the inlet oil temperatures stabilized at 228°F. Then, with the transmission still operating at 680 horsepower (30 horsepower through the tail rotor, lift and bending loads applied to the main rotor mast), valve A was opened and valve B was closed (reference Figure 38), allowing the oil to be pumped from the transmission. After complete loss of the oil supply, the transmission continued to operate for 54 minutes before torque was lost due to a failure of the lower planetary stage. Figure 41 is a plot of the lower planetary ring gear temperatures recorded during the loss-of-lube test. At failure, the ring gear temperature was 1210°F. Figures 41 through 49 show temperature plots of various components during the 54-minute loss-of-lube test and Figure 50 shows transmission temperatures at failure.

Disassembly of the transmission following the 54-minute loss-of-lube test revealed that the failure was very similar to the one that occurred after the 25-minute loss-of-lube test of optimized transmission configuration number 1. Figures 51 through 71 show various components following the loss-of-lube test of optimized transmission configuration number 2. The teeth had been stripped from all four of the lower planetary pinions. The pinions were also oblong and deformed. Some of the rollers retained within the pinions were skewed sideways. The tangs that retain these rollers had softened and rolled over on the bearing cages. The lower planetary sun gear teeth had softened and the center portion of the teeth had been rolled over. The upper and lower ring gears were covered with a carbon residue, but the teeth had not softened like the lower planetary pinions or the lower sun gear.

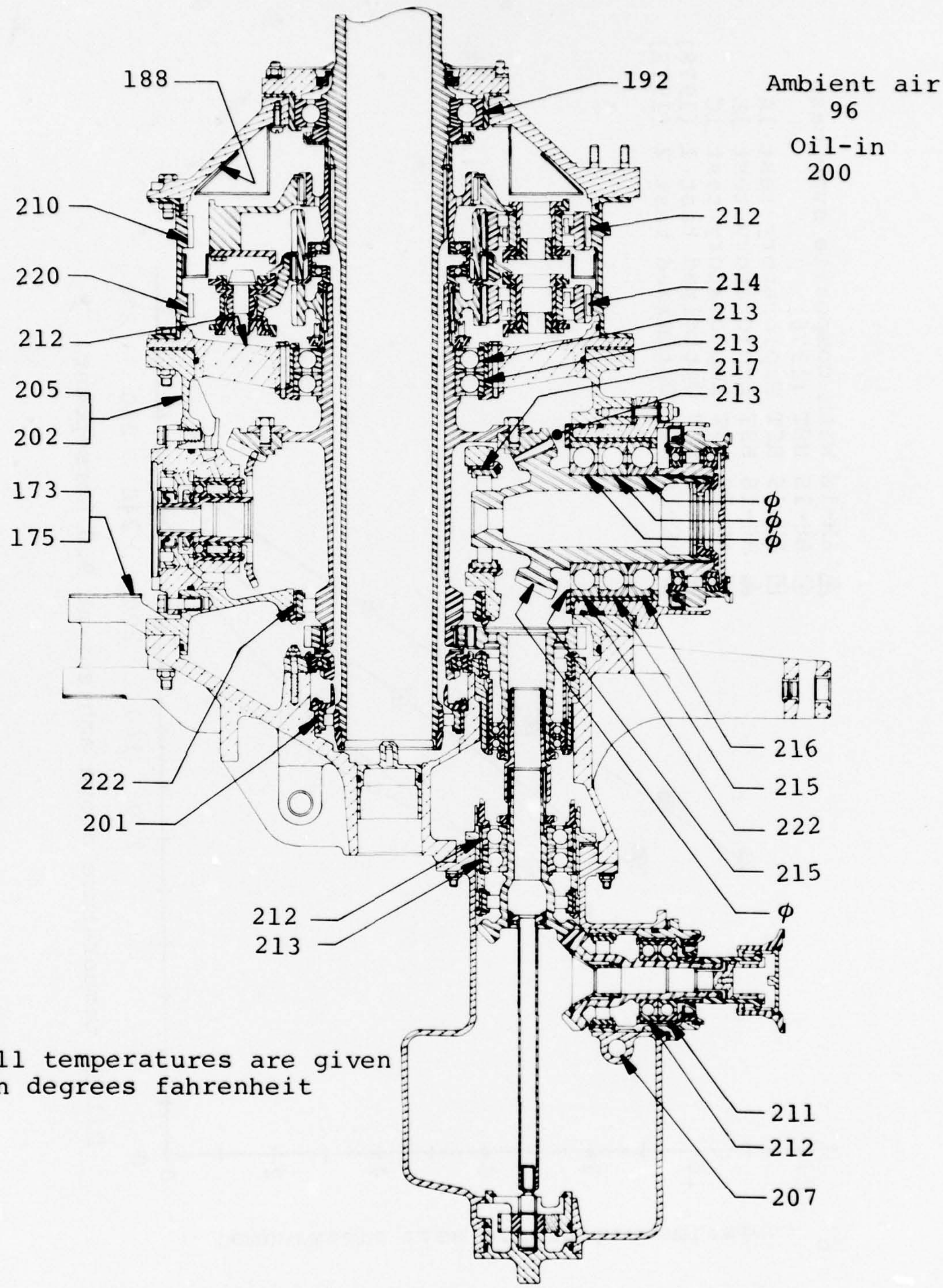


Figure 39. Stabilized temperatures for optimized transmission configuration number 2 at 200°F oil-in, 950 horsepower (Step 1 of Table 6).

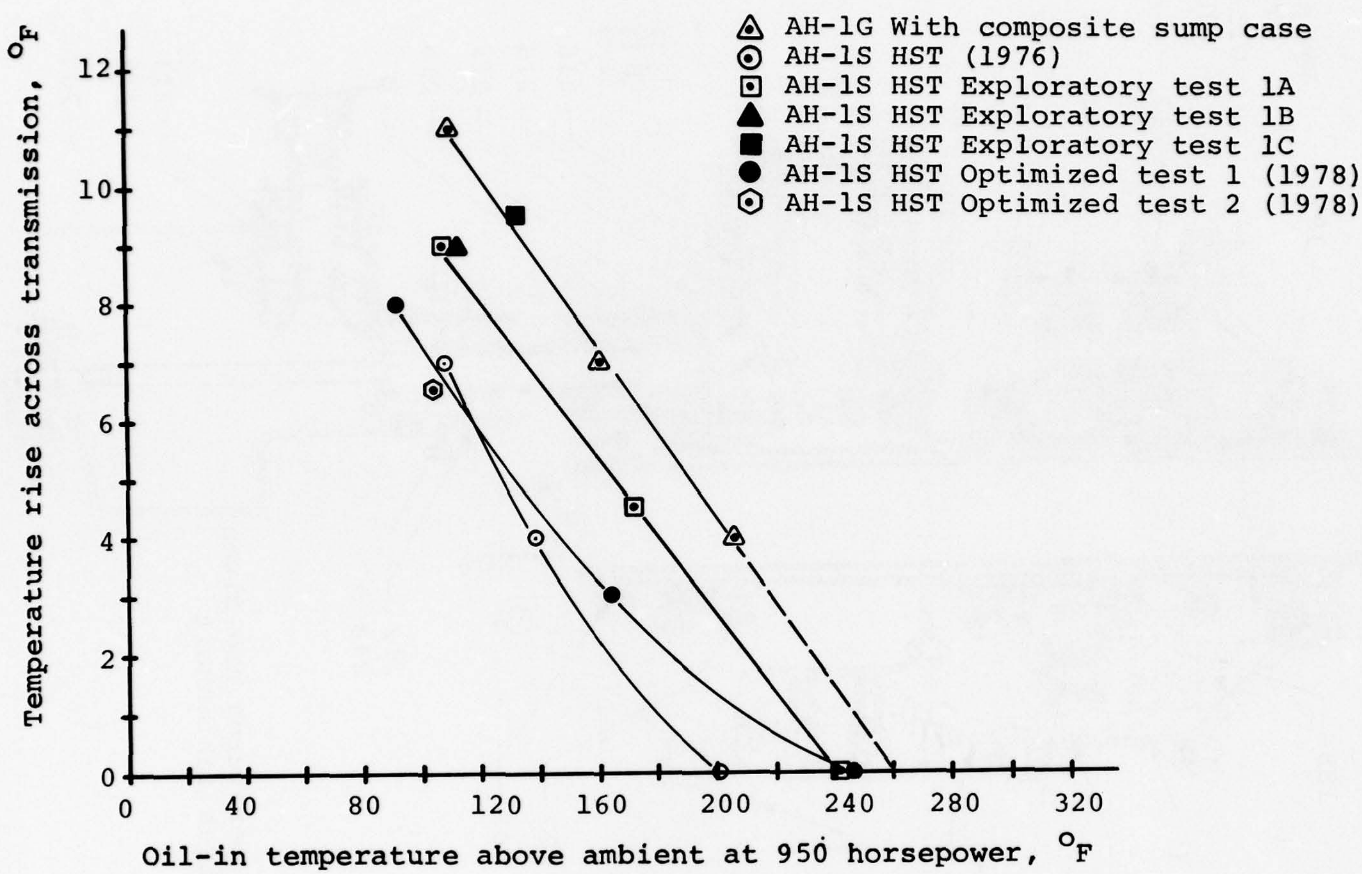


Figure 40. Oil cooler requirements of various HST configurations at 950 horsepower.

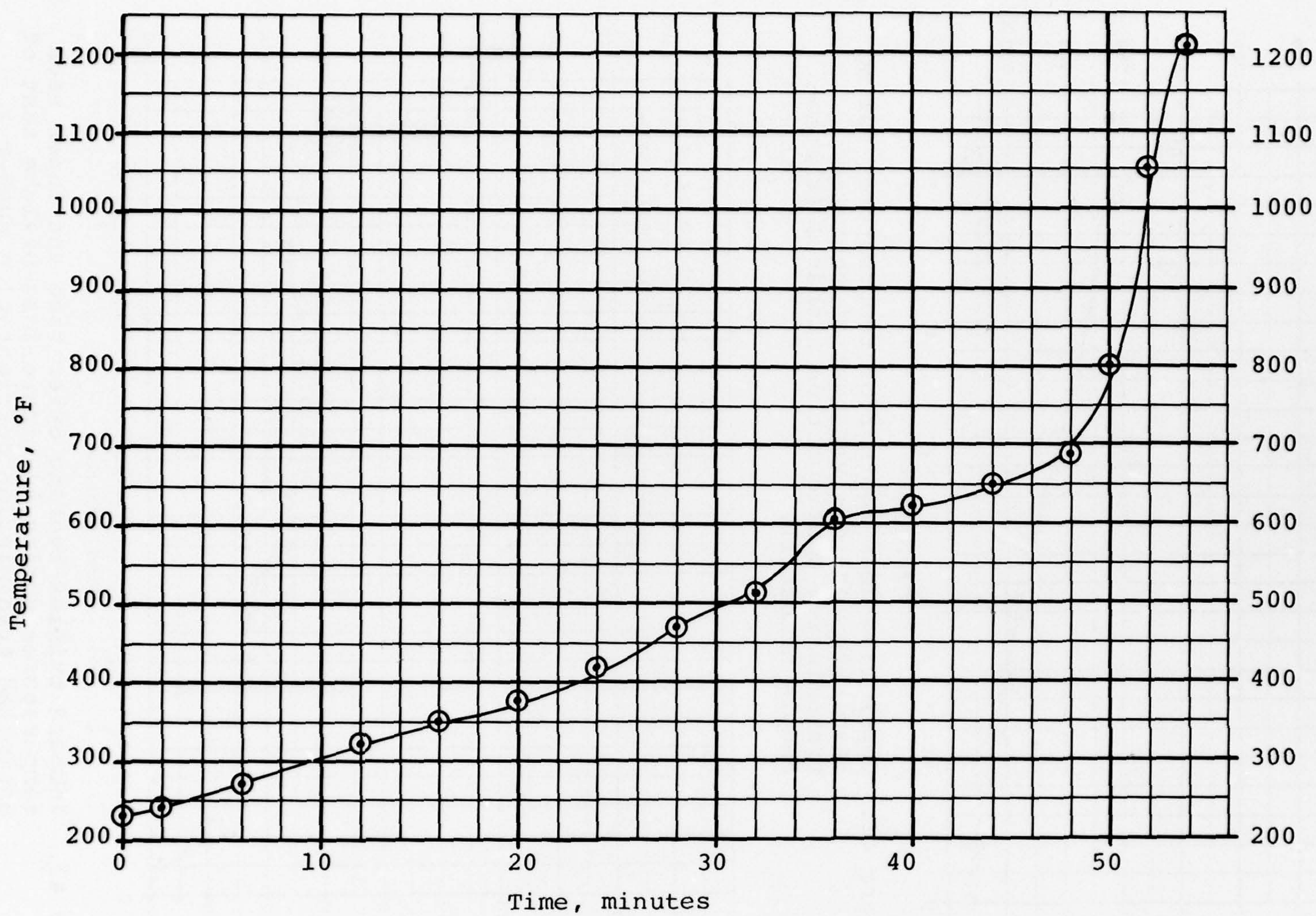


Figure 41. Lower ring gear tooth root temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple number 13).

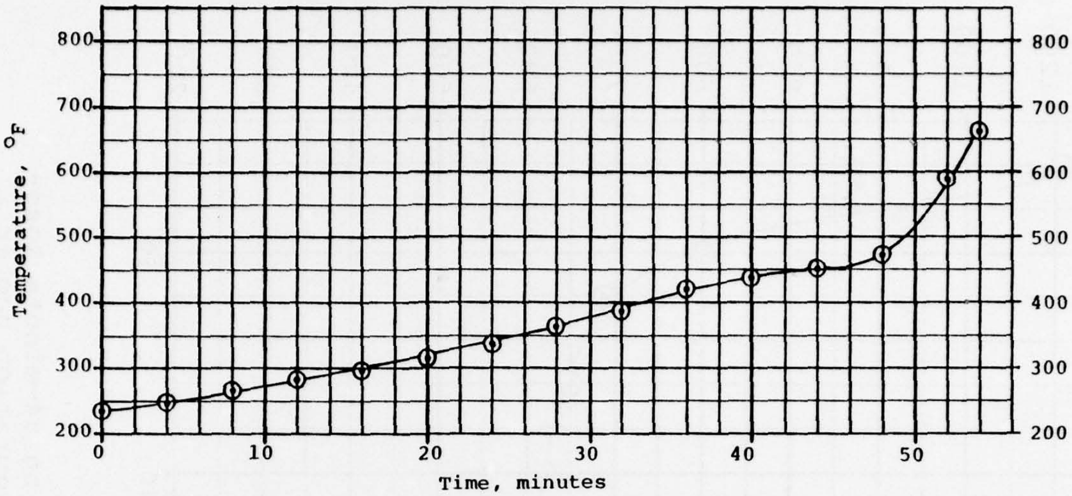


Figure 42. Upper ring gear tooth root temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple number 12).

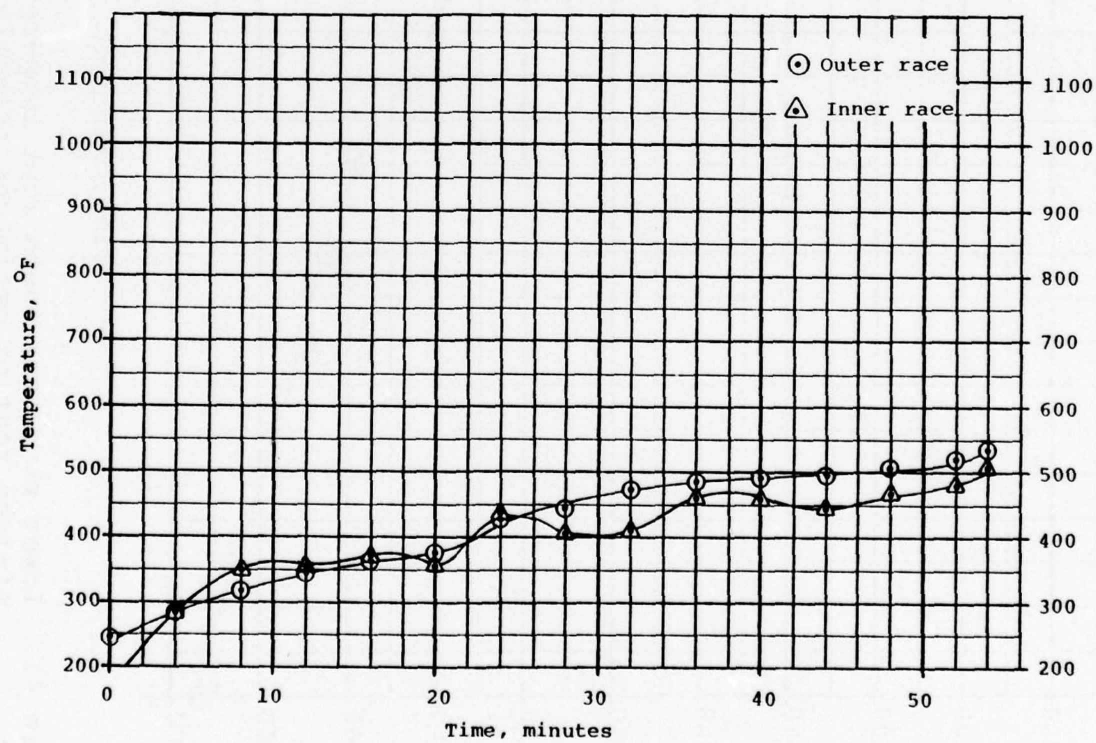


Figure 43. Inboard triplex bearing outer race and inner race temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple numbers 18 and 21).

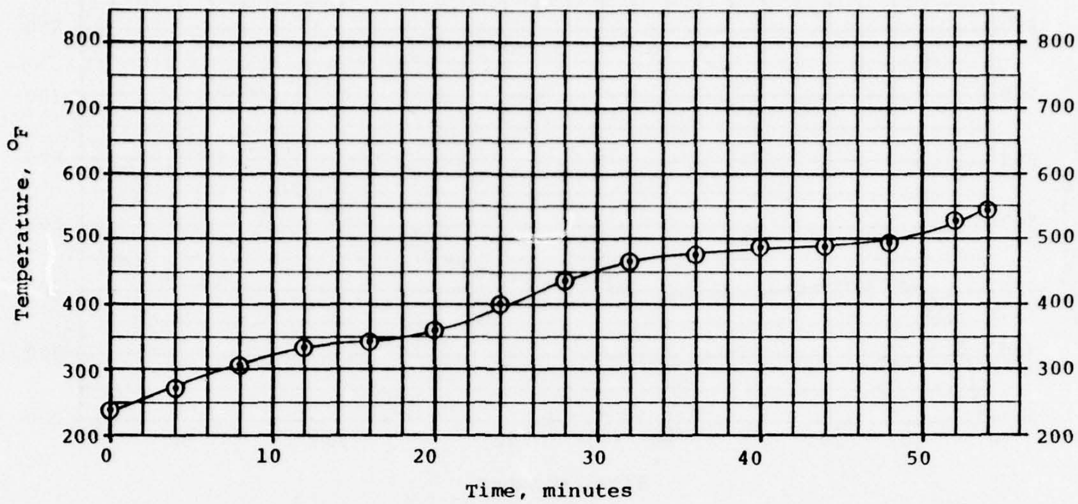


Figure 44. Outboard triplex bearing outer race temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple number 20).

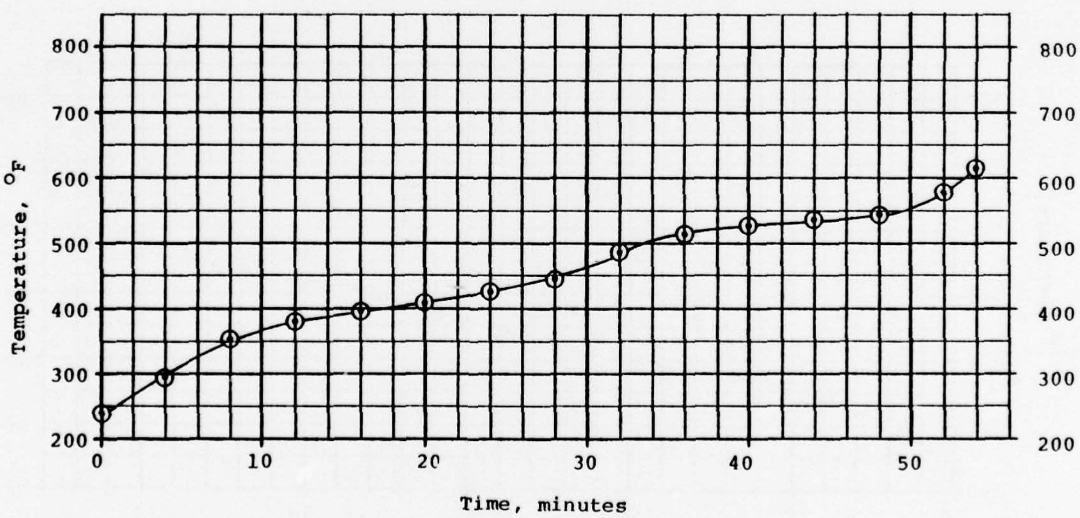


Figure 45. Input pinion roller bearing temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple number 5).

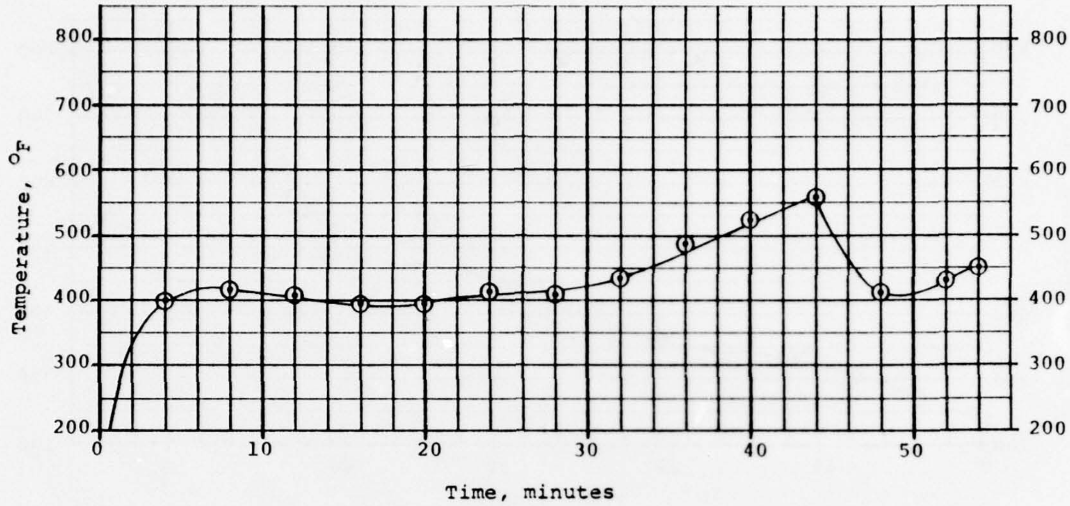


Figure 46. Input pinion tooth root temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple number 25).

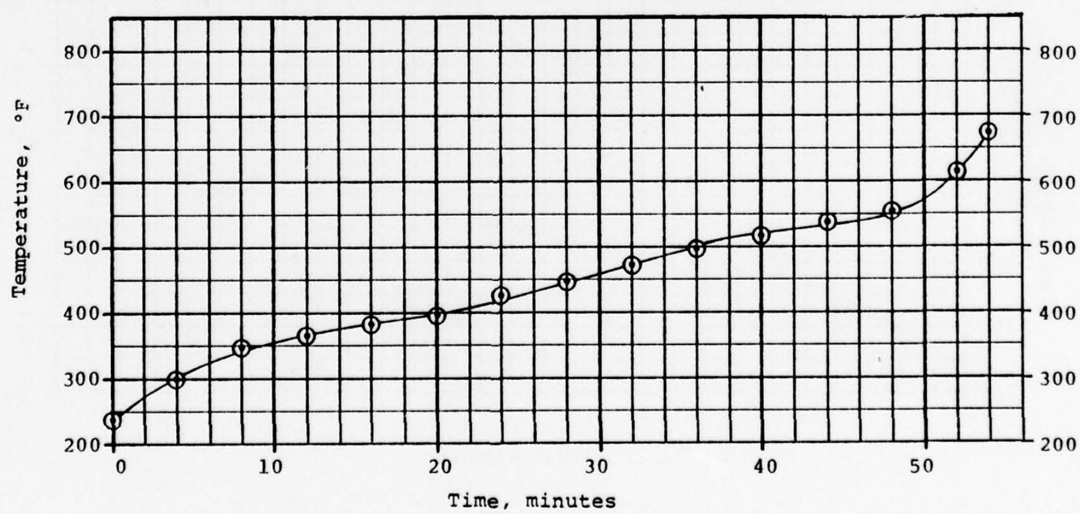


Figure 47. Input bevel gear set out-of-mesh airstream temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple number 32).

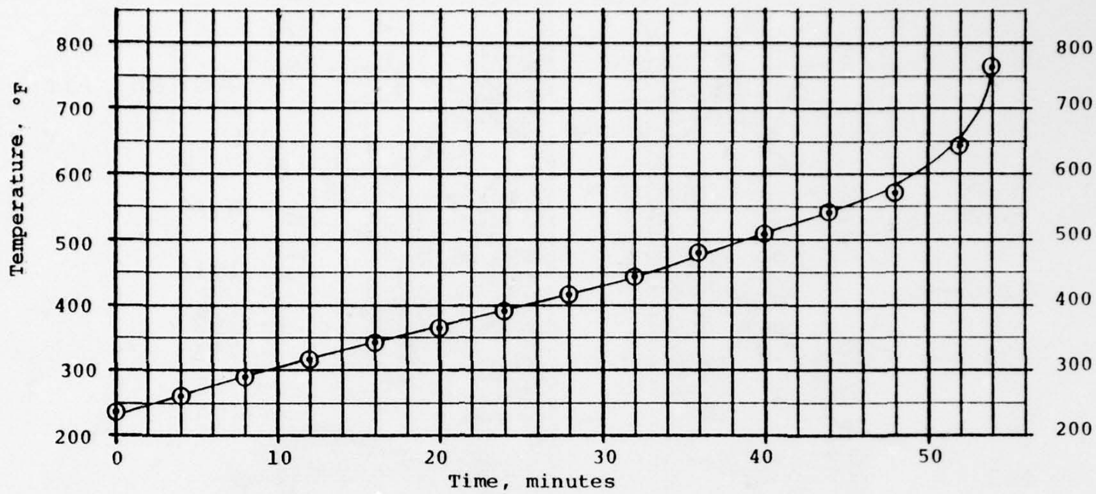


Figure 48. Gearshaft duplex bearing outer race temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple number 3).

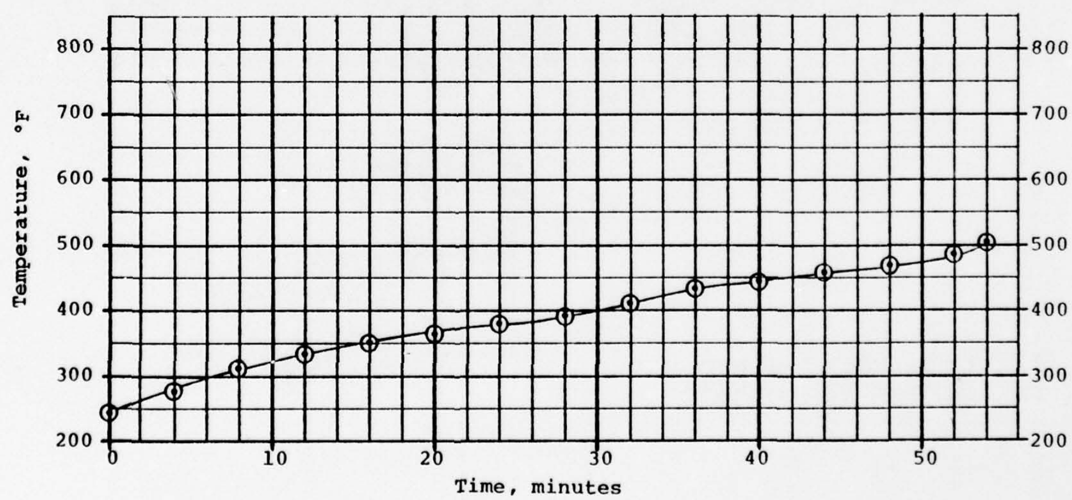


Figure 49. Gearshaft roller bearing outer race temperatures during 54-minute loss-of-lube test of optimized transmission configuration number 2 (thermocouple number 6).

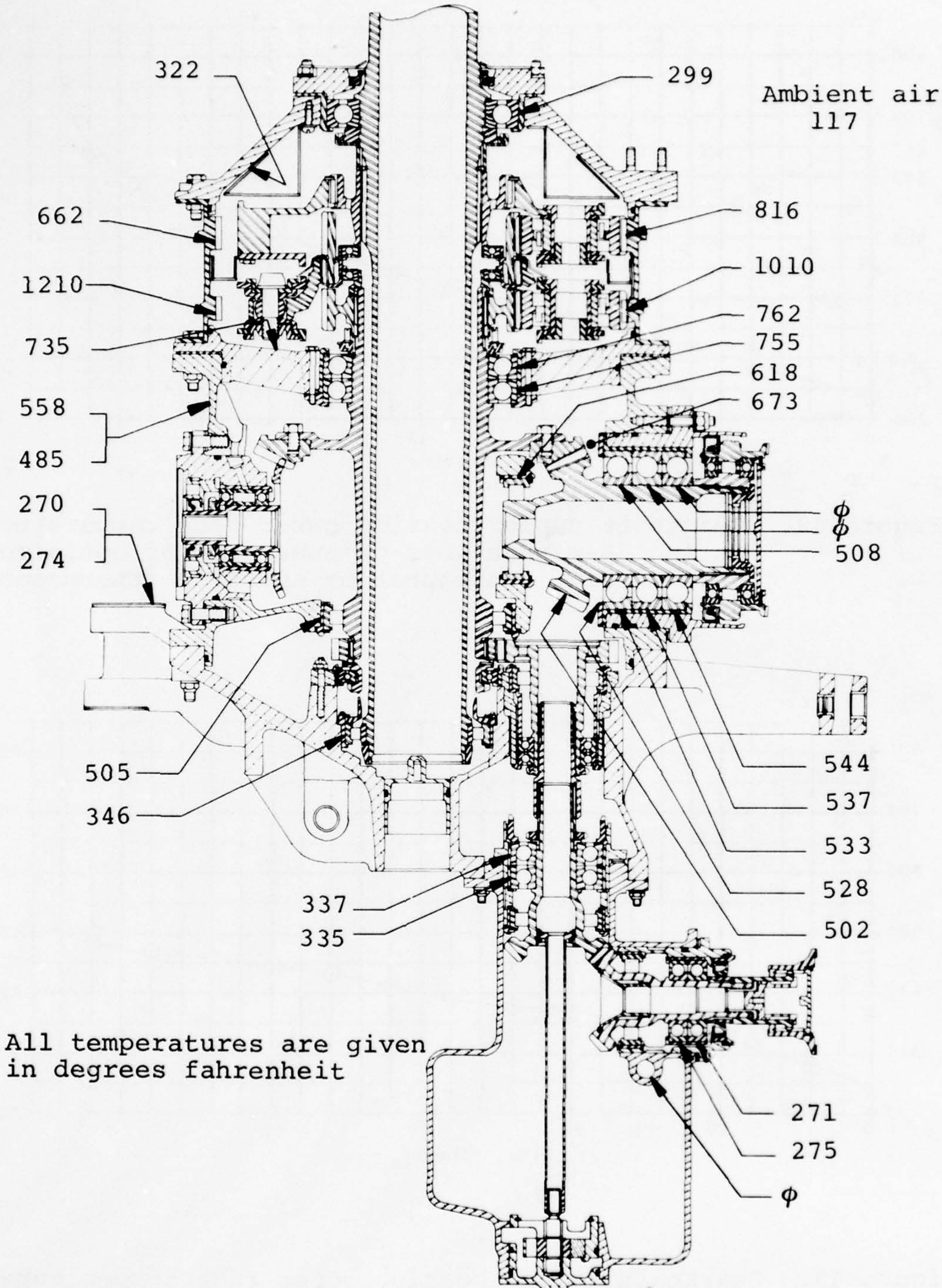


Figure 50. Transmission temperatures at failure after 54-minute loss-of-lube test of optimized transmission configuration number 2.

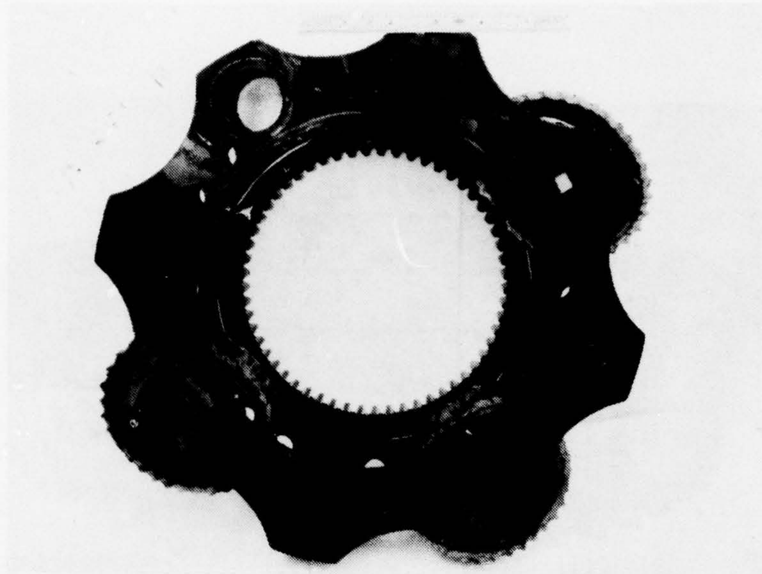


Figure 51. Lower planetary assembly after 54-minute loss-of-lube test of optimized transmission configuration number 2.

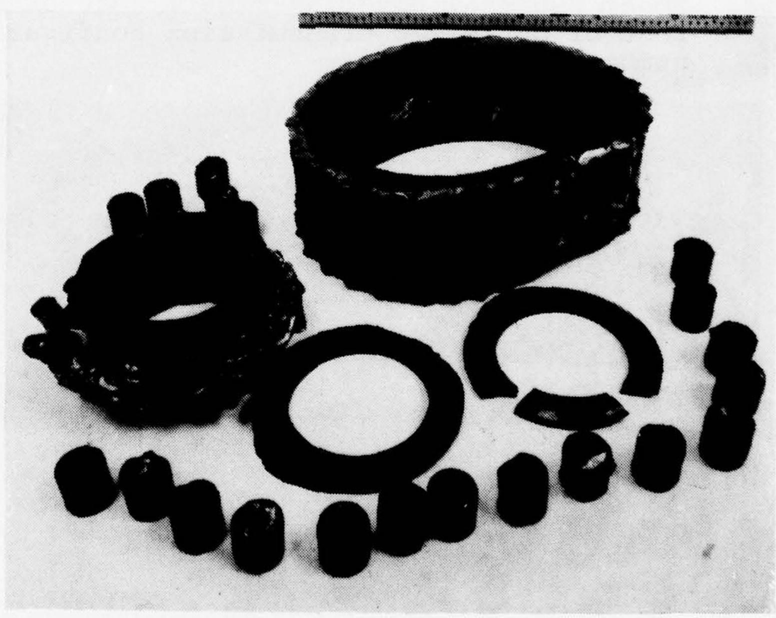


Figure 52. Lower planetary pinion, bearing inner race, rollers, roller guides, and retainer after 54-minute loss-of-lube test of optimized transmission configuration number 2.

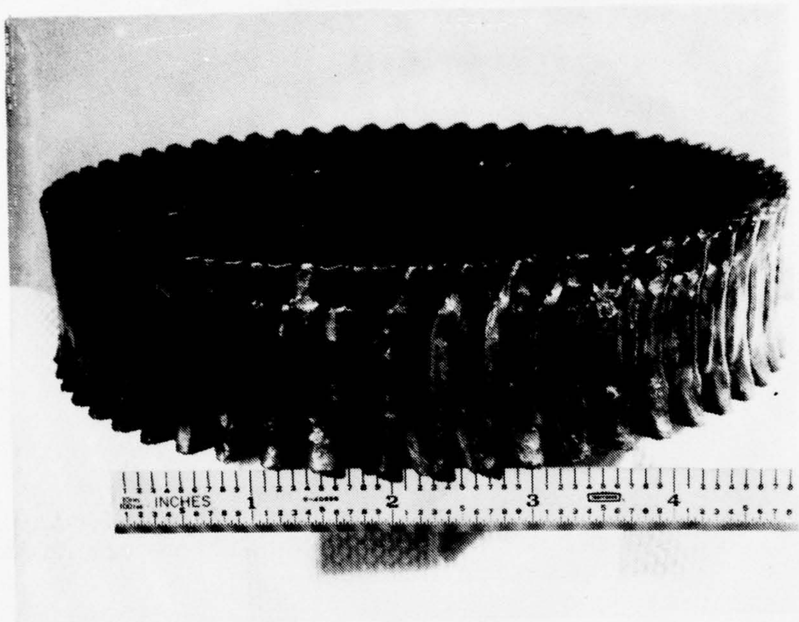


Figure 53. Lower sun gear after 54-minute loss-of-lube test of optimized transmission configuration number 2.

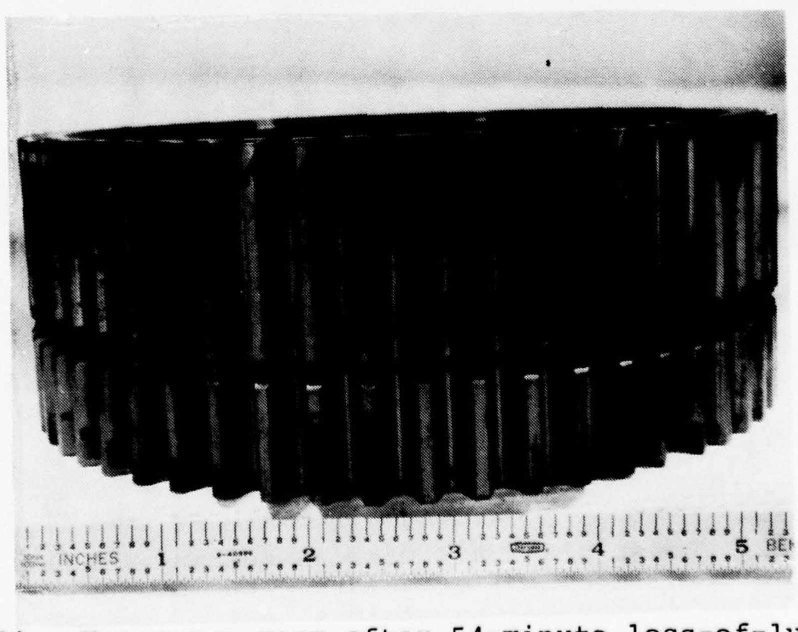


Figure 54. Upper sun gear after 54-minute loss-of-lube test of optimized transmission configuration number 2.

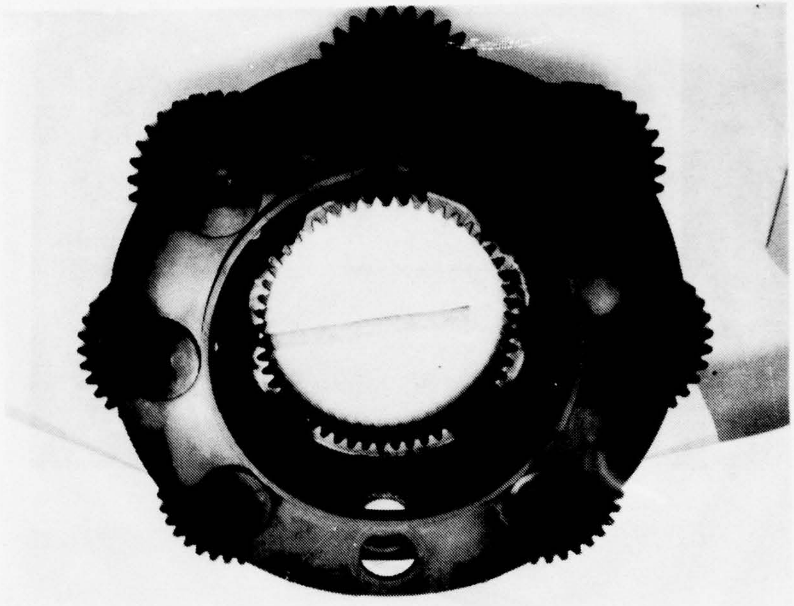


Figure 55. Upper planetary assembly after 54-minute loss-of-lube test of optimized transmission configuration number 2.

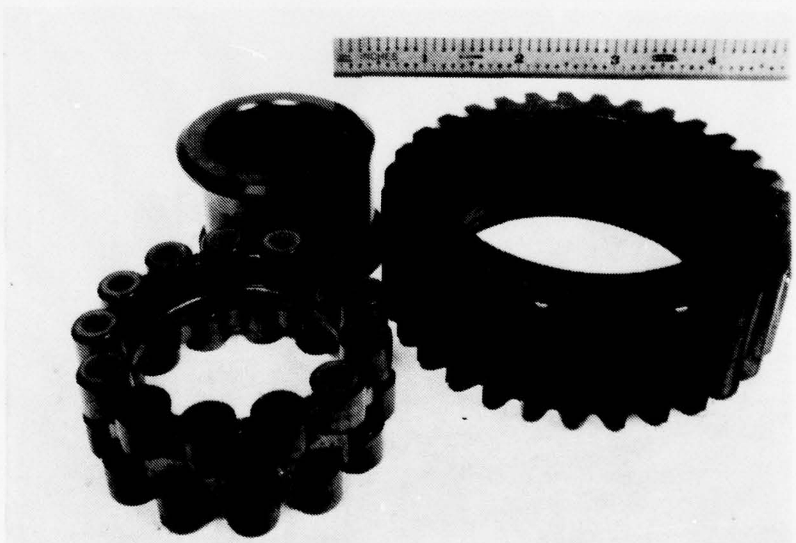


Figure 56. Upper planetary pinion, bearing inner race, rollers, roller guides, and retainer after 54-minute loss-of-lube test of optimized transmission configuration number 2.

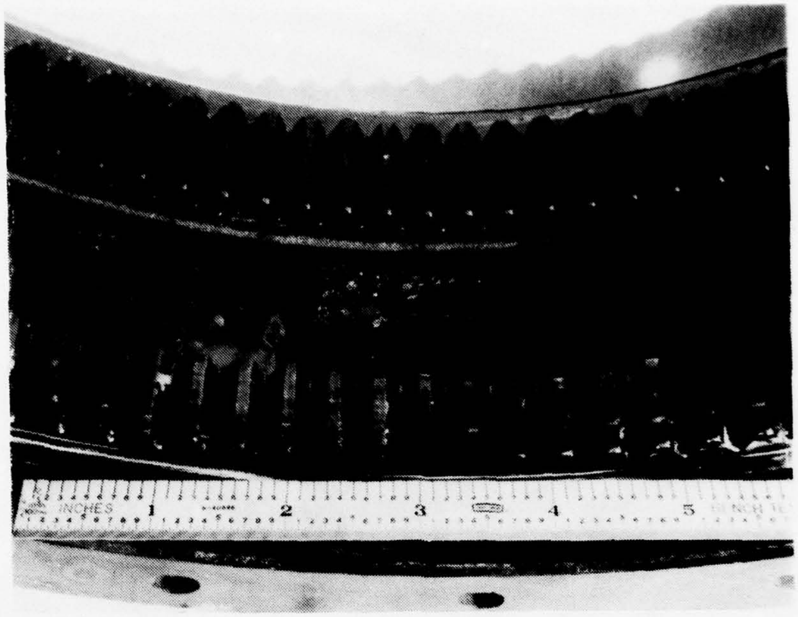


Figure 57. Upper ring gear (top) and lower ring gear teeth (bottom) after 54-minute loss-of-lube test of optimized transmission configuration number 2.

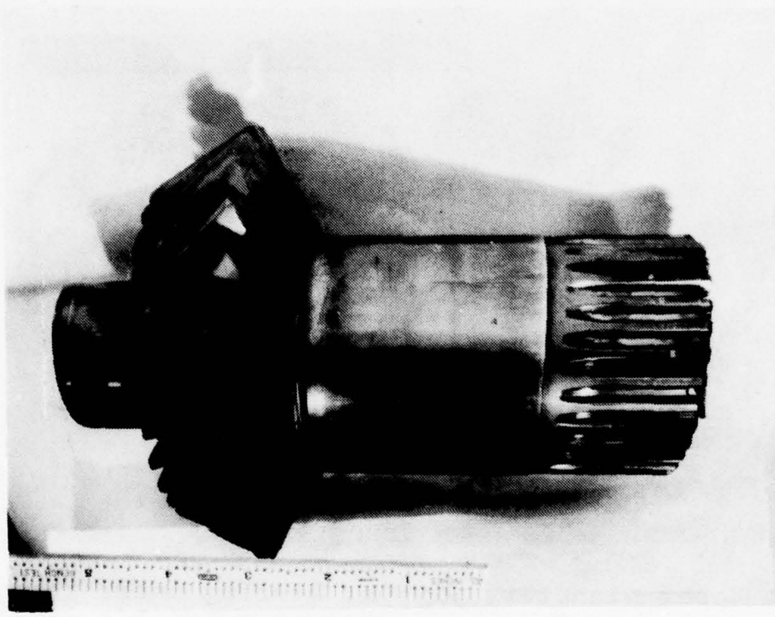


Figure 58. Main input pinion after 54-minute loss-of-lube test of optimized transmission configuration number 2.

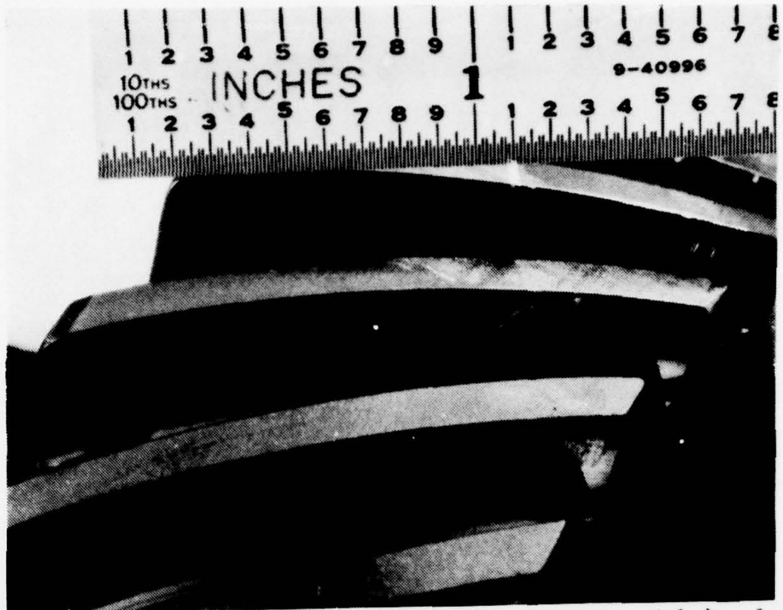


Figure 59. Main input pinion teeth (drive side) showing light scoring after 54-minute loss-of-lube test of optimized transmission configuration number 2.

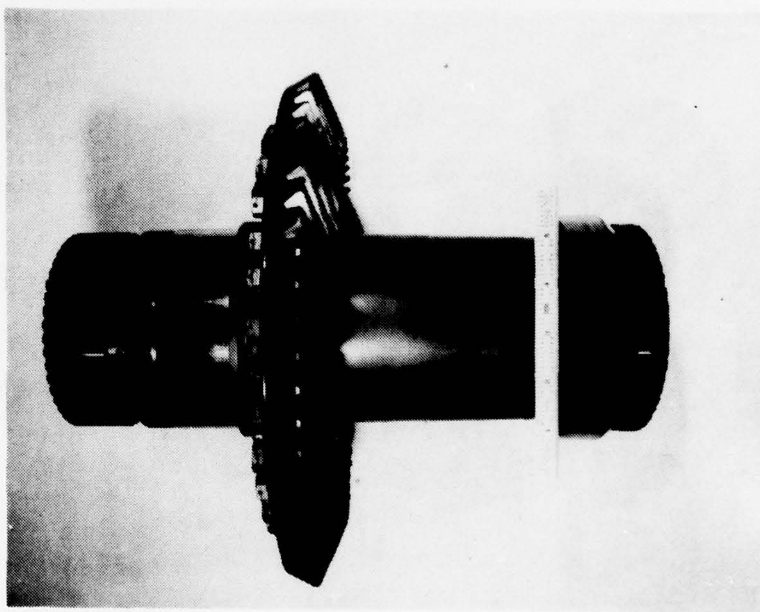


Figure 60. Main input gear and gearshaft after 54-minute loss-of-lube test of optimized transmission configuration number 2.

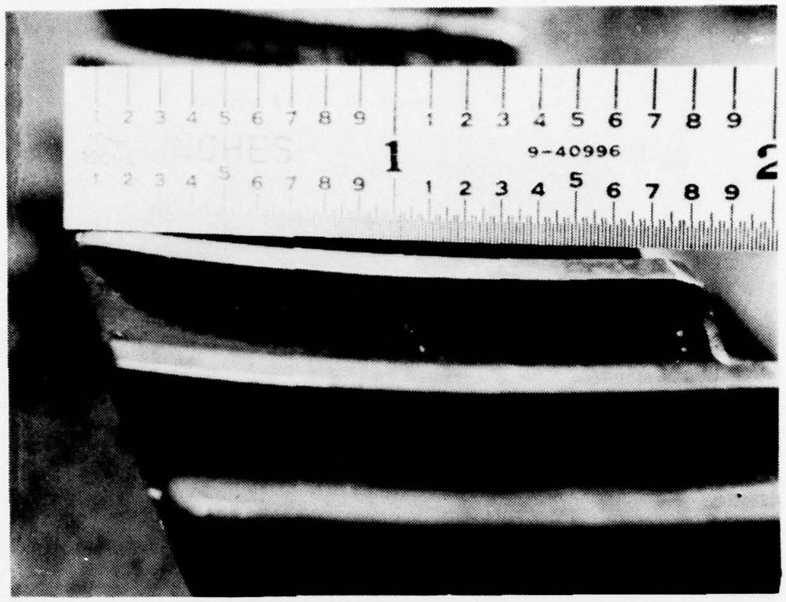


Figure 61. Main input gear teeth (drive side) showing light scoring after 54-minute loss-of-lube test of optimized transmission configuration number 2.

Figure 62. Main input triplex bearing after 54-minute loss-of-lube test of optimized transmission configuration number 2.

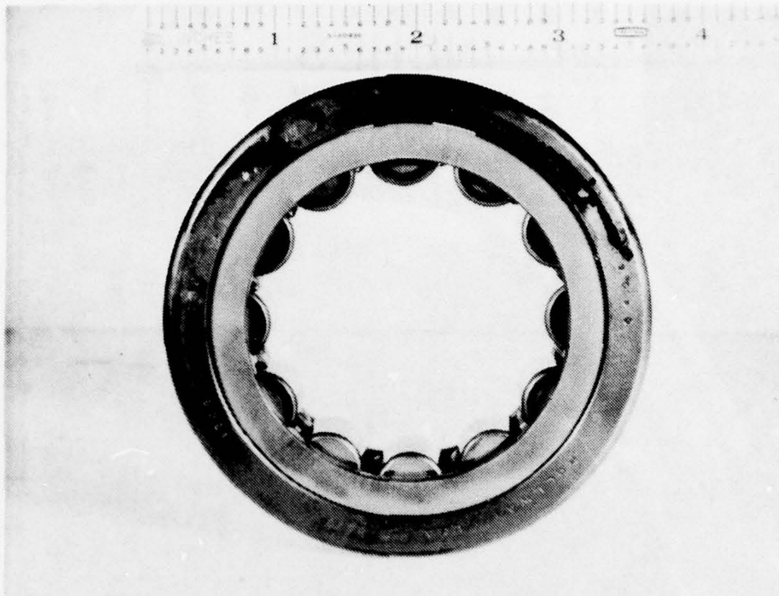


Figure 63. Main input pinion roller bearing after 54-minute loss-of-lube test of optimized transmission configuration number 2.

Figure 64. Main gearshaft duplex bearing after 54-minute loss-of-lube test of optimized transmission configuration number 2.

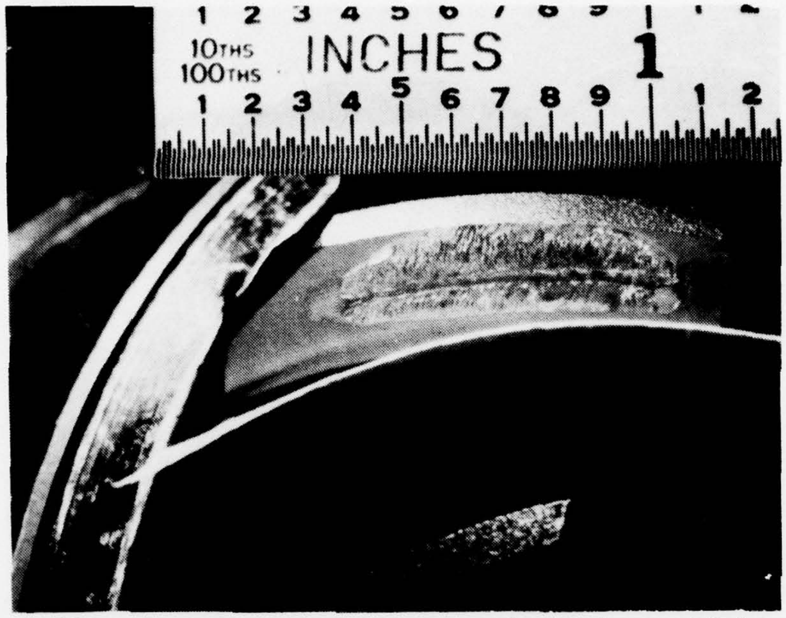


Figure 65. Sump output gear teeth (drive side) showing light scoring after 54-minute loss-of-lube test of optimized transmission configuration number 2.

Figure 66. Fan accessory duplex bearing after 54-minute loss-of-lube test of optimized transmission configuration number 2.

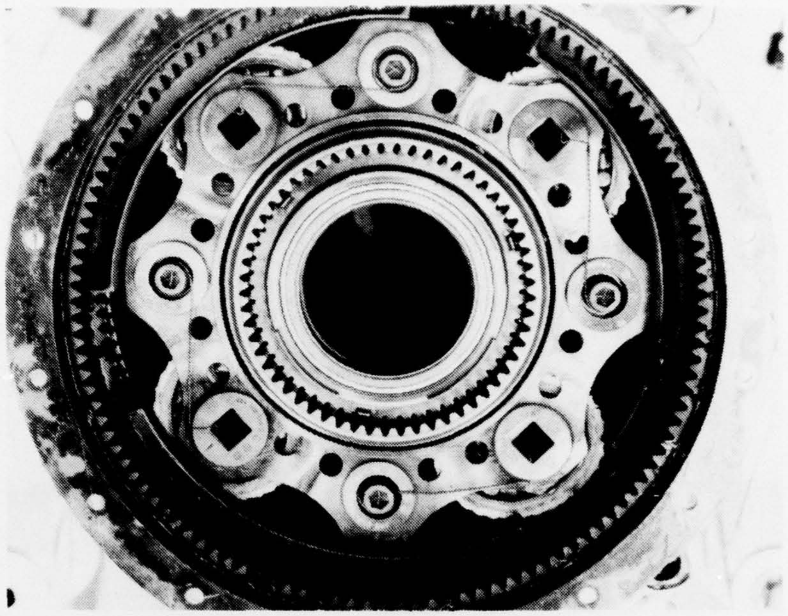


Figure 67. View looking into ring gear case showing lower oil collectors after 54-minute loss-of-lube test of optimized transmission configuration number 2.

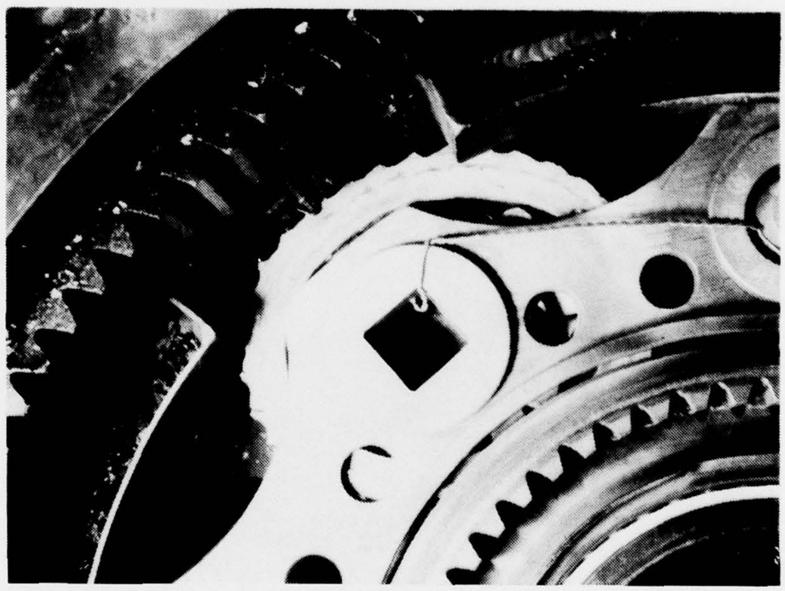


Figure 68. View looking into ring gear case showing debris in lower oil collectors after 54-minute loss-of-lube test of optimized transmission configuration number 2.

Figure 69. View showing lower oil collector in ring gear case after 54-minute loss-of-lube test of optimized transmission configuration number 2.

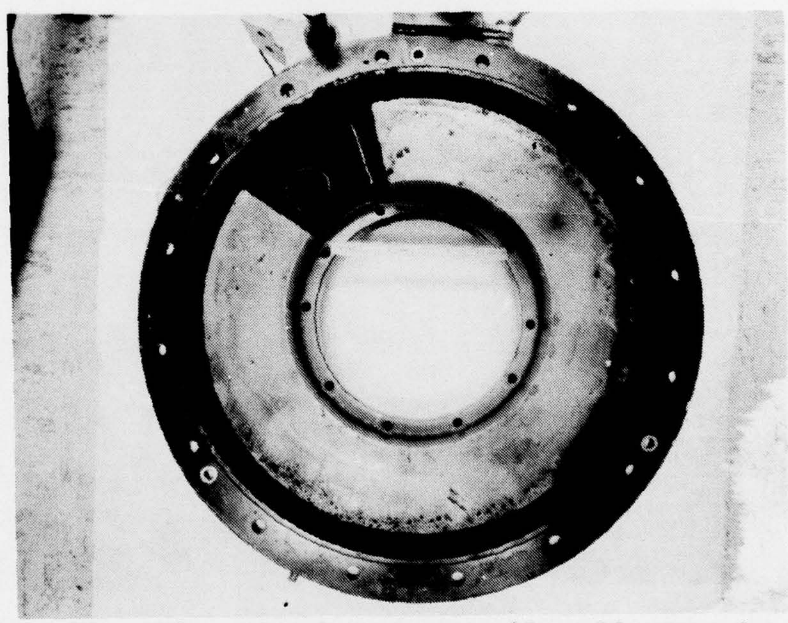


Figure 70. View showing upper oil collector in top case after 54-minute loss-of-lube test of optimized transmission configuration number 2.

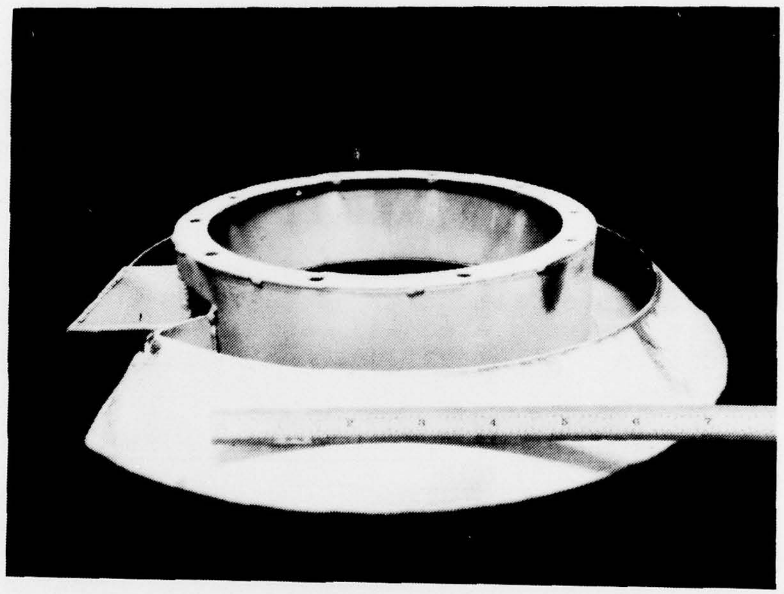


Figure 71. Upper oil collector after 54-minute loss-of-lube test of optimized transmission configuration number 2.

The upper planetary assembly was dry when disassembled, but it was still fully functional. There was no evidence that gear clearance or bearing clearances had been lost. Both the upper and lower planetary support bearing turned roughly when removed from the transmission.

The teeth of the main input bevel gear set were moderately scored after the 54-minute loss-of-lube run. The triplex ball bearing and the roller bearing that support the main input pinion still had slight traces of oil when removed from the transmission. The balls and rollers (which were made of M-50 steel) had a bluish tint as a result of the high temperature operation, but the bearings still turned smoothly and, seemingly, suffered no real damage.

The lower oil collectors were dry and contained some debris. The felt on the back of the lower oil collectors was burned black and was brittle due to the high temperature of the ring gear case during the loss-of-lube test number 2. The upper oil collector was drained of lubricant but was covered by an oil film.

The tail rotor drive spiral bevel gear set located in the sump area was scored slightly. Both gears and bearings were still oily in the sump area and, aside from the slightly-scored condition of the gear set, no other damage was apparent.

DISCUSSION OF RESULTS OF OPTIMIZED TRANSMISSION CONFIGURATION NUMBER 2 TESTING

The 54-minute loss-of-lube test of optimized transmission configuration number 2 achieved the goal of 30 minutes of loss-of-lube operation of an AH-1S transmission. The 54 minutes is a significant time period beyond the 30-minute goal, thus it provides a high level of confidence that 30 minutes of loss-of-lube run time could be achieved in an AH-1S helicopter in actual operation.

The lower planetary stage modification and the addition of upper and lower oil collectors to the test transmission for optimized configuration loss-of-lube test number 2 was effective in maintaining transmission operation for 18 minutes after the lower ring gear temperature reached 600°F (see Figure 72). This was an improvement over the previous tests in which the transmissions lasted 4 to 10 minutes once the 600°F lower ring gear temperature was attained. The use of the oil collectors accounted for the improved high-temperature performance of the test number 2 optimized transmission configuration. The lower planetary is an intermediate stage

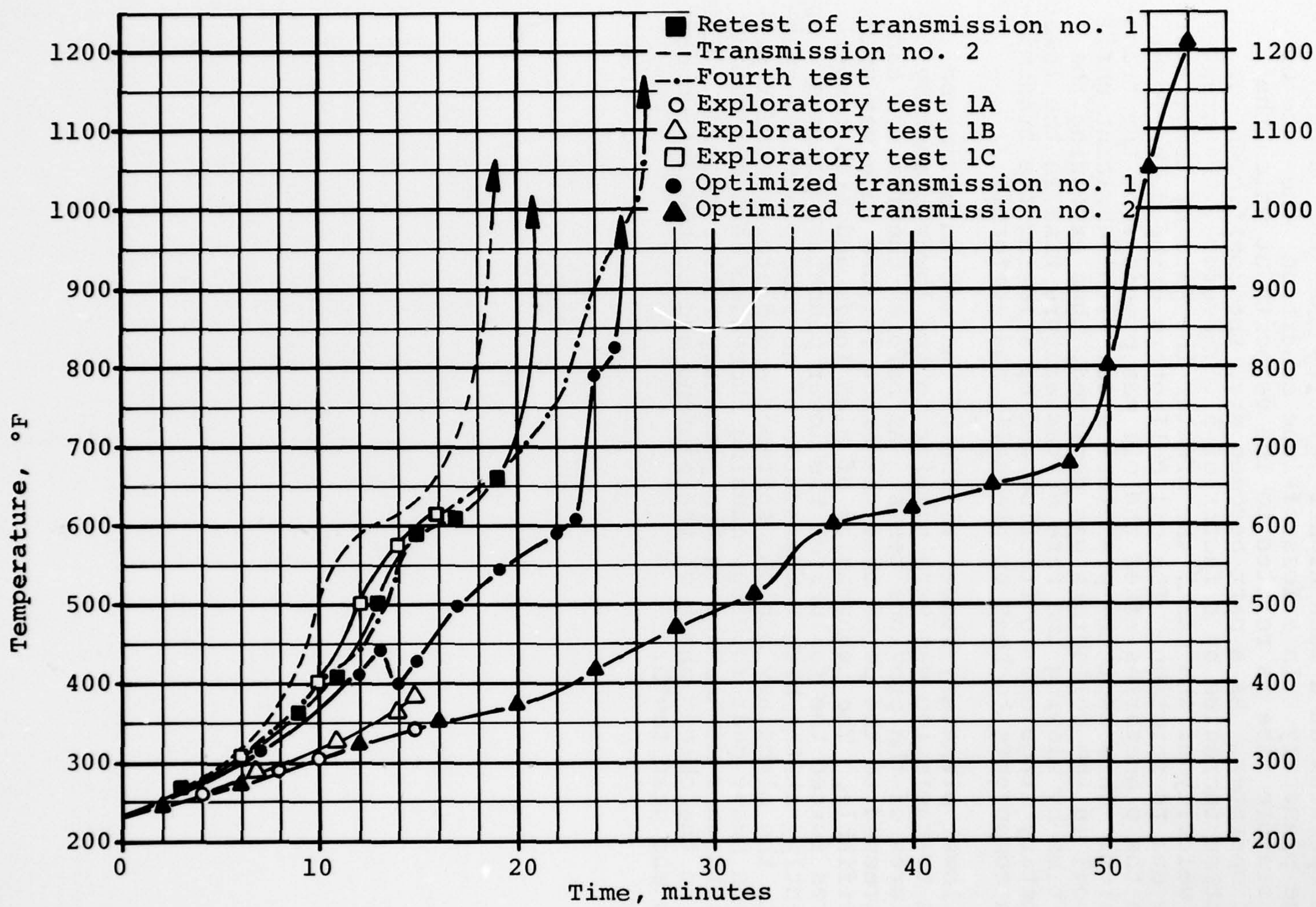


Figure 72. Comparison of lower ring gear tooth root temperatures from the loss-of-lube tests.

that operates at a much higher velocity than the output stage planetary. In a loss-of-lube condition, the rate of temperature rise is related to the velocity at which the part operates. As a part becomes dry, the coefficient of friction increases by a factor of 5. Therefore, the greater the velocity of the part, the greater the rate of temperature rise due to friction. The oil collectors dripped lubricant onto the planetaries after the oil was pumped from the transmission. This kept the planetaries wet with lubricant until the oil in the collectors was depleted, thus extending the run time by slowing the rate of temperature rise in the lower planetary stage due to friction and by allowing the transmission components to heat up gradually and uniformly.

The lower planetary stage failure of the second optimized test transmission was very similar to the lower planetary failures of the previous tests. As before, the failure had progressed to the point that the exact failure mode was unidentifiable. The combination of high loads and high temperatures forced the failure of the lower planetary pinions. Apparently, at the high temperatures of no-lube planetary operation, the planetary pinions softened and distorted under predesign heavy gear loading, causing increased heat generation at both gear meshes and in the planetary roller bearing. This led to the oblong shape of the pinions and to the failed bearings and gear teeth.

SUMMARY OF TESTS PERFORMED

Table ~ is a brief summary of the testing performed under this contract. The program goal of 30 minutes loss-of-lube capability of the transmission was exceeded on the last test. The modification to the standard AH-1S transmission to achieve the 30-minute capability would be as follows:

- Shim the main input spiral bevel gear set to a minimum of 0.012-inch backlash and a maximum of 0.019-inch backlash
- Modify the main input triplex bearing with increased internal clearance by increasing the outer race curvature
- Install a silver-plated steel retainer in place of the bronze retainer in the main input pinion roller bearing
- Install silver-plated steel retainers in place of the nylatron retainers in the main gearshaft duplex bearing
- Install a silver-plated steel retainer in place of the bronze retainer in the gearshaft roller bearing
- Install silver-plated steel retainers in place of the bronze retainers of the lower planetary roller bearings
- Install bronze retainers in place of the nylon retainers of the upper planetary roller bearings
- Install silver-plated steel retainers in place of the bakelite retainers of the planetary ball bearings
- Install planetary roller guides made of M-50 steel instead of AISI 52100 steel
- Install planetary rollers made of M-50 steel instead of AISI 52100 steel in the lower planetary
- Install oil collectors above the upper planetary and between the upper and lower planetaries
- Modify top case to attach upper oil collector
- Modify oil jet to spray stream of oil into upper oil collector

The 30-minute capability would be based on a power level of 60 percent of MCP. A temperature probe on the lower ring

TABLE 7. SUMMARY OF LOSS-OF-LUBE TESTS

Test	Percent MC Power	Loss-Of-Lube Run Time (Minutes)	Failure Mode
Transmission no. 1	84	7	Main input bevel pinion teeth
Retest of transmission no. 1	84	21	Lower planetary stage
Transmission no. 2	84	19	Lower planetary stage
Fourth test	84	26.5	Lower planetary stage
Optimized transmission no. 1	60	25	Lower planetary stage
Optimized transmission no. 2	60	54	Lower planetary stage

gear would be an excellent indicator to the pilot of the operating condition of the transmission under loss-of-lube conditions. Once the lower ring gear temperature exceeded 600°F, an immediate landing would be necessitated.

A comparative weight analysis of the modified components in an AH-1S high survivable transmission versus the components in a standard AH-1S transmision is shown in Table 8. The AH-1S high survivable transmission used in optimized loss-of-lube test number 2 weighs approximately 4.2 pounds more than the standard AH-1S transmission.

TABLE 8. AH-1S HIGH SURVIVABLE TRANSMISSION WEIGHT ANALYSIS

COMPONENT	QTY/ XMSN	STANDARD TRANSMISSION		AH-1S HIGH SURVIVE XMSN		XMSN WEIGHT (lb)
		UNIT WEIGHT (lb)	WEIGHT/ XMSN (lb)	UNIT WEIGHT (lb)	WEIGHT/ XMSN (lb)	
Triplex Bearing	1	10.3	10.3	10.3	10.3	0
Input Pinion Roller Bearing	1	1.3	1.3	1.3	1.3	0
Gearshaft Duplex Bearing	1	6.3	6.3	7.09	7.09	+0.79
Gearshaft Roller Bearing	1	2.16	2.16	2.2	2.2	+0.04
Planetary Support Bearing	2	0.82	1.64	0.92	1.84	+0.2
Upper Planetary BRG Retainer	8	0.025	0.2	0.175	1.4	+1.2
Lower Planetary BRG Retainer	4	0.174	0.7	0.12	0.48	-0.22
Planet Bearing Roller Guide	24	0.069	1.66	0.069	1.66	0
Lower Planet BRG Roller Set-	4	0.44	1.76	0.44	1.76	0
Screws and Washers to Attach Upper Oil Collector	10	-	-	0.015	0.15	+0.15
Oil Jet	1	0.1	0.1	0.1	0.1	0
Upper Oil Collector	1	-	-	1.3	1.36	+1.36
Lower Oil Collector	3	-	-	0.23	0.69	+0.69

TOTAL = 4.21 lb

CONCLUSIONS

The AH-1S HST test program led to the following conclusions:

- The internal component improvements for the AH-1S transmission system tested under this program extended the loss-of-lube capability of this transmission from about 7 minutes to over 30 minutes. The use of oil collectors above the lower planetary stage had a very noticeable, beneficial effect on the loss-of-lube run time. The use of M-50 steel for the lower planetary rollers and roller guides enhanced the high-temperature operation of the lower planetary stage. Standard planetary gear mesh clearances (0.0035 to 0.0065 inch) appear sufficient in loss-of-lube running of this transmission.

- A minimum of 0.012-inch backlash and a maximum of 0.019-inch backlash in the main input spiral bevel gear set is required to achieve a 30-minute loss-of-lube capability for this gear set.

- The narrow face width, crowned, lower sun gear did not change the failure mode to a less severe condition as anticipated based upon the results of the prior AH-1G HST program (reference USAAMRDL TR-76-8). However, the AH-1G HST program used an emergency lube system that allowed the components to heat up gradually and uniformly. Perhaps the failure mode would be changed to the stripping of the narrow lower sun gear teeth if the narrow lower sun gear was used in conjunction with the oil collectors that allow a gradual and more uniform heat buildup in the transmission. More testing would have to be performed before a conclusion could be drawn.

- The bronze retainers in the upper planetary stage demonstrated excellent operating characteristics during the loss-of-lube running on this program and are adequate at this location.

RECOMMENDATIONS

As a minimum program designed to significantly improve the loss-of-lube survivability of the AH-1S helicopter, the internal component improvements listed in Section 7 of this report should be incorporated on the AH-1S transmissions.

A less severe lube-loss failure mode for the AH-1S transmission is desirable. A program to accomplish this should be conducted and should consider the suggestion offered in Section 8 of this report: narrow face width, crowned, lower sun gear in conjunction with the oil collectors.

The thermal tests conducted under this program indicate that elimination of the transmission oil cooler would be feasible if the transmission cases, gears, bearings, and other components, as well as the lubricant itself, could operate continuously at temperatures approaching 400°F. Programs to effect these capabilities should be undertaken.